

18

New Energy Times Archive

Peter Upton, D. de Stroo.

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10/13/89

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Dick -

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$\checkmark 5.5 \times 10^{-22}$ ✓

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23.5 M - 18

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Draft - Oct. 10, 1989

FUSION PRODUCTS

I. INTRODUCTION

The nuclear fusion of deuterium has been studied intensively for over 40 years. The reaction between two low energy deuterium nuclei can proceed in three ways:

- (a) $D + D \rightarrow {}^3He + n + 3.269 \text{ MeV}$
- (b) $D + D \rightarrow {}^3H + p + 4.037 \text{ MeV}$
- (c) $D + D \rightarrow {}^4He + \text{gamma} (23.847 \text{ MeV})$

The reactions (a) and (b) have been studied down to deuteron energies of a few keV and the cross sections found to be equal to within 10%. In the interaction of deuteron beams with heavy ice or metal deuteride targets, almost one 2.45 MeV neutron is produced (with an accompanying 3He) for every triton (with an accompanying proton). This near-equality of neutron and proton branches of the $D + D$ reaction, shown in figure 1, is a reflection of the basic symmetry of nuclear forces between proton and neutron, disturbed only slightly at the MeV energies of the emerging particles by the Coulomb interaction, which is not symmetrical between proton and neutron. The cross sections for reaction (c) are very small -- on the order of 10^7 lower than the first two.

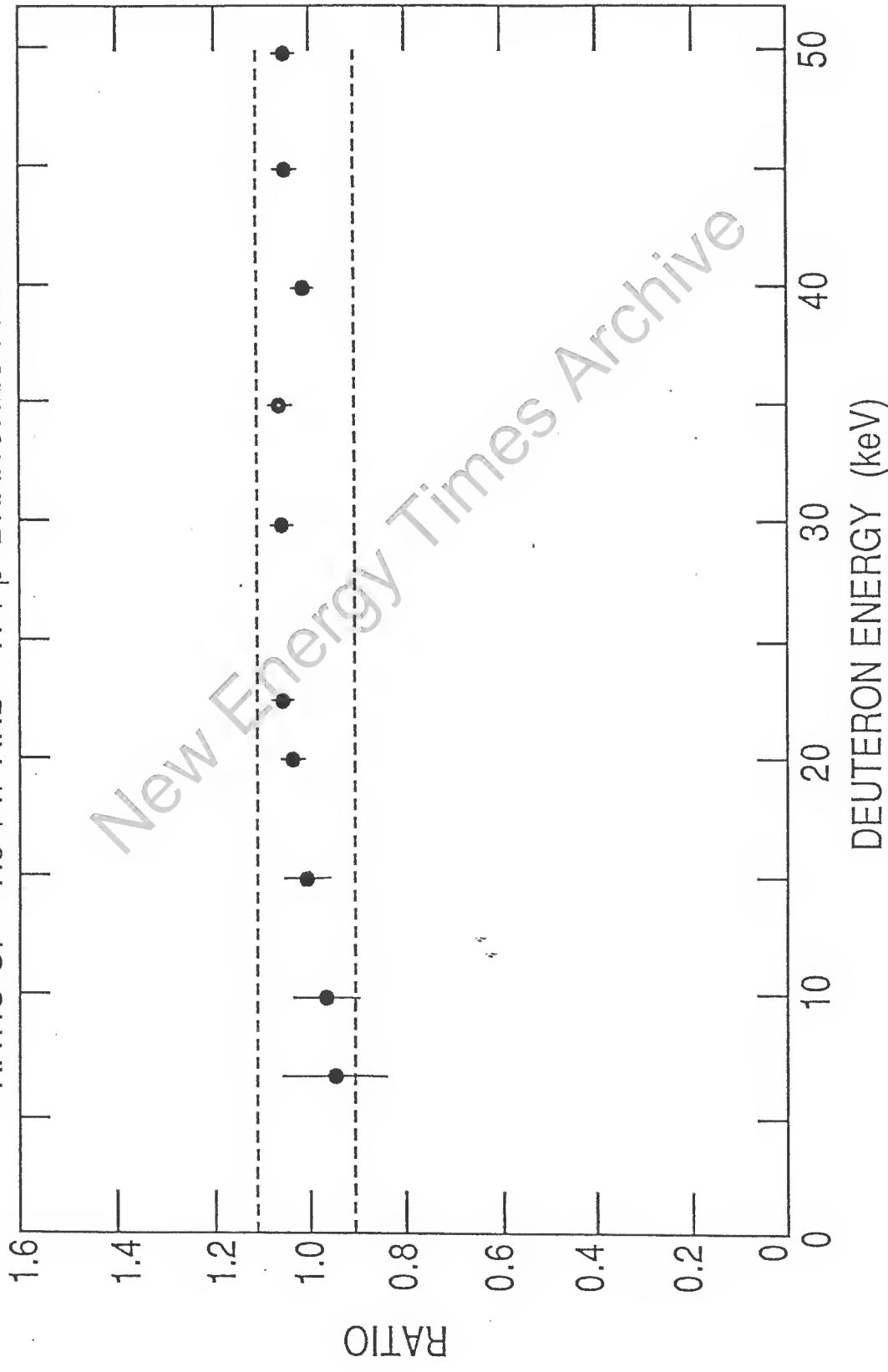
All nuclear reactions at low energies between two deuterons are retarded by the Coulomb repulsion between the positively charged nuclei -- the penetration of the repulsive Coulomb barrier changes exponentially with bombarding energy: for instance the measured cross section for reaction (b) changes from 0.2 microbarns at 2.7 keV to 35 millibarns at 100 keV. But the ratios for the three reactions appear to be constant below 100 keV.

Any fusion between deuterium nuclei must lead to detectable fusion products. For reaction (a) neutrons are the most easily detected product, by direct counting. For (b) the protons or tritons can be detected by direct counting, and the accumulated tritium could also be identified by its radioactivity, albeit with lower sensitivity. Neutron counting is perhaps again the most useful technique here, since neutrons must be produced by the energetic tritons interacting with other deuterons in the material at the rate of 1 neutron for every 10,000 to 50,000 tritons. Reaction (c) leads to readily detectable high energy gamma rays and 4He ; the latter may be identified by mass spectroscopic measurements, whose sensitivity is low -- though the 10^{17} levels implied by 1 watt of heat should be readily observable.

In the following we summarize the experimental evidence on these fusion products. First we discuss the plausibility of reactions at room temperature and the issue of whether the constancy of the three reaction modes is a reasonable extrapolation to very low energies. Then the data on neutrons, charged particles, gamma rays and tritium are summarized. Finally, some comments are included on the more exotic explanations, and geophysical evidence is summarized on proposed cold fusion in the interior of the earth.

ANL-P-19,711

RATIO OF $^3\text{He} + \text{n}$ AND $^3\text{H} + \text{p}$ BRANCHES FROM D + D



II. THE REACTION PROCESS

Fusion reactions can occur only if during a nuclear collision the Coulomb barrier is surmounted or, at low energies, penetrated so that the nuclei approach each other within about 10^{-12} cm. This distance is some 10000 times smaller than the typical separations of atoms in ordinary matter. The penetration of the barrier at low energies takes place through a well-understood quantum mechanical phenomenon called tunneling that allows fusion to occur in collisions far less violent than might be required otherwise.

In the thermonuclear fusion that occurs in stars and in laboratory "hot fusion" experiments, very high temperatures provide the violent collisions required to produce fusion. However, in the so-called cold fusion experiments, it is claimed that the penetration of the barrier through ~~quatum~~ mechanical tunneling has somehow become so effective as to allow fusion to occur even at room temperatures. Further, some of the experimenters claim that the nuclear process is changed by some unspecified mechanism so as to alter dramatically the nature of the reaction products. Each of these claims must be understood as separate and equally surprising.

Some simple calculations serve to illustrate how remarkable the claim of fusion at room temperatures really is. The fusion rate for the two deuterium nuclei in a deuterium molecule (where they are even closer than they are when embedded in a metal) results in one fusion per year in a solar mass of deuterium. Further, the fusion of protons and deuterons is 10^9 times faster than the D + D reaction claimed to have been observed (although it is still extraordinarily slow). There is no known mechanism by which these rates could be enhanced by the 40-50 orders of magnitude required to agree with the reported observations.

One commonly invoked mechanism for enhancing cold fusion rates is screening by "heavy" electrons. It is true that endowing the electron with a hypothetical mass some 5-10 times larger than it actually has would enhance fusion rates sufficiently to agree with most cold fusion claims [Ko]. It is also true that there are "heavy fermion" materials whose thermodynamic properties at very low temperatures are characteristic of quasiparticles with masses many times those of a free electron. However, this phenomenon is understood as involving long-wavelength excitations in which strong correlations "dress" electrons near the Fermi surface. As such, heavy fermions extend over many lattice sites. Because the tunnelling in nuclear fusion occurs at distances smaller than one lattice site, only the short-wavelength "bare" electron excitations are relevant for screening, and cannot enhance the fusion rate significantly.

IIa. The D + D Branching Ratios.

The relative rates of reactions (a), (b), and (c) are called the branching ratios and are a crucial issue in the discussion of some cold fusion claims. These reactions have been studied in laboratory experiments using accelerators for deuteron energies above a few keV [Kr]; the smallness of both cross sections prevents reliable measurements at lower energies. The ratio between the two rates exhibits a weak energy dependence and is near 1.0 at the lowest energies as seen in figure 1. Data from muon-catalyzed D + D fusion [Bal], which probes an even lower energy range, is still consistent with nearly equal rates.

A branching ratio of more than one million would be required to explain experiments that claim to observe high fusion rates (either through heat or tritium production) without a corresponding high neutron flux. As "cold fusion" is thought to occur at energies on the order of eV, this is not directly ruled out by the data discussed above. However, there is no known mechanism for inducing such a rapid energy-dependence in the branching ratio. The Oppenheimer-Phillips process involving the Coulomb break-up of the deuteron has sometimes been invoked in this regard. However, this approximation is not valid at low energies in the D + D system.

IIb. The Gamma Branch.

Some researchers have hypothesized that the $D + D \rightarrow {}^4He + \text{gamma}$ (23.847 MeV) reaction, which is ordinarily some 10^7 times weaker [Bar] than reactions (a) and (b) in which two fragments are produced, somehow dominates in cold fusion situations. To be consistent with the lack of neutrons, a very large enhancement of the gamma branch by a factor somewhere in excess of 10^{13} would be required. We know of no way whereby the atomic or chemical environment can effect such an enhancement, as this ratio is set by phenomena on a length scale some 10^4 times smaller than the atomic scale.

Even if there were such an enhancement, the absence of observed high-energy electromagnetic radiation (photons, positrons, or fast electrons) rules out such a mechanism. While direct coupling to the lattice through unspecified mechanisms has been invoked to suppress such radiation, any such coupling must occur through the electromagnetic field and would result in some observable high-energy radiation.

IIc. The p + D Reaction.

It has been suggested that an alternative fusion process could be the reaction



for which the penetration factors are still overwhelmingly small at room temperature, but somewhat less so than for the D + D process [Ko]. This reaction must produce a readily observable gamma ray and if it is to account for 1 watt of heat, then it should also produce 3He in observable concentrations.

IId. Estimate of Secondary Yields from Fusion Products.

i) **Neutrons from tritium.** The tritons produced in reaction (b) are produced with an energy of 1.01 MeV. This energy must be lost in the immediately surrounding material, which in the case of an electrolytic cell is either the Pd electrode saturated with deuterium, or heavy water. The tritons will therefore bombard the deuterium in the surrounding material. The t+d reaction is a rich source of neutrons, with a cross section that reaches 5 barns at 0.12 MeV, then falls to about 0.7 barns at 0.5 MeV, and reaches slightly below 0.3 barns at 1 MeV. For the 1.01 MeV tritons from the D + D reaction one may assume an average cross section of about 1.2 barns. For tritons that are stopped in PdD this translates into a neutron yield between 0.15 and 0.2×10^{-4} neutrons per triton;

for tritons stopping in heavy water there are about 0.9×10^{-4} per triton.

ii) Coulomb excitation of Pd by protons. The even Pd isotopes (104, 106, 108, 110) with abundances of 11, 27, 26, 12 % have first-excited 2^+ states at 555, 512, 434, 374 keV and $B(E2)$ values between 0.5 and 0.8 barns. The cross sections for Coulomb excitation are in the vicinity of 20 to 50 mb and thus the yields expected are 2 to 5×10^{-6} per proton. In palladium the half thickness for absorption of these gamma rays is about 4 mm, in water it is several cm.

In terms of power, there must be about 10^8 /sec secondary neutrons per watt of fusion, even if direct neutron production is completely suppressed and all the reaction goes into tritium production. Under these conditions there must also be slightly under 10^7 secondary photons per second, of well defined energies, in the 500 keV range.

III. NEUTRONS

IIIa. Detection.

As discussed above, neutrons are a major product of D + D fusion. Neutrons are very convenient particles to detect, since they interact only with the nuclei of atoms and so can emerge from reaction vessels of substantial size unscathed and without having lost any energy. Similarly, large counters can be used without the problem of thin entrance windows, since neutrons enter into the volume of the counter without difficulty. Some simple facts about neutron detection are summarized in Appendix A.

IIIb. Selection of Data.

This should be handled like Calorimetry chapter.

In what follows, we have tried to use published material, where available, or material prepared for publication and presented at formal meetings or as preprints distributed without restriction as to citation. It is important to include not only positive results, that claim the detection of neutrons, but also the negative ones, that have attempted to replicate the experimental procedure of the former and failed to detect neutrons at a level of sensitivity substantially better than the positive results.

IIIc. Initial claims.

The University of Utah (UU) group in its initial publication [Fle] claimed the detection of neutrons from D + D by virtue of the gamma ray emitted by the capture of the moderated neutron in the water bath surrounding the electrolytic cells. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper, considerably narrower than is possible with this type of detector, and with internal inconsistencies in the energy scale.

Very careful to state unbiased handling of data by our Panel

These very questions were taken up by a group at MIT, [Pe] who showed that the photo peak at 2.2 MeV obtained at MIT from Cf spontaneous fission neutrons moderated in water and radiatively captured on protons is accompanied by other peaks from natural background that enable one to calibrate the energy, and

successive interchange between UU and MIT groups in the scientific literature has demonstrated that the claimed detection of neutrons by the proton capture gamma ray at UU was an artifact of the experimental apparatus.

The original publication from Brigham Young University (BYU) [Jo] presented the detection of neutrons as the sole experimental evidence for the existence of cold nuclear fusion. The neutrons were detected in a two-stage neutron counter -- first by the proton recoil in organic scintillator, followed within a few tens of microseconds by a signal from the capture of the moderated neutron on boron viewed by the same photomultipliers. This double detection of a single neutron serves substantially to reduce the ambient background due to gamma rays, although there remains background in the experiment due to gamma rays and to real neutrons from cosmic rays* and other sources. The group at BYU has chosen to attempt to vary the experimental conditions in order to obtain a greater rate of D + D fusion, and so has not presented much more data than the original paper on the detection of neutrons with that counter. In fact, BYU has been working in collaboration with other groups, notably at LANL [Me], and also with a group at Yale University. The original claim of neutron detection five standard deviations above the background is somewhat reduced in statistical strength if one considers the degrees of freedom that are fixed by the presentation of a peak in one of a number of experiments and at a particular energy, and also the possible fluctuation in the cosmic-ray neutron background. Ordinarily, however, such a result can be improved through improved shielding or by moving to an underground site.

Typical of the latter is work presented by the group at Sandia National Laboratory, [Ald] in which a site was found with substantially less background and results presented for a limit on neutrons produced in electrolytic fusion. Similar results from the Frejus tunnel in France were also presented in Santa Fe. [DeC1]

Many claims have been made for the production and detection of neutrons produced in electrochemical cells, but these claims have almost all been withdrawn or moderated by the discovery of difficulties with the counter -- particularly with the BF₃ counters used. In some cases, the counters are sensitive to humidity; in others to microphonic noise (vibration); or to other afflictions. A summary of some of the limits on neutron fluxes reported, compared to the flux reported by the BYU group, is shown in Table I.

IIId. Dry Fusion.

Results presented in April 1989 by a group at Frascati [DeN] opened an entirely new opportunity for the observation of D + D cold nuclear fusion. In this work, deuterium gas at 60 atmospheres pressure (60 bar) was allowed to contact titanium lathe turnings in a stainless steel reaction vessel. That allowed the temperature of the sample to be varied either by heating or by cooling. No neutrons were observed from the hydriding reaction at room temperature or at elevated temperature, when viewed by a nearby BF₃ counter.

*Additional care is needed as the rate of cosmic ray neutrons can fluctuate by 20% or more with variations in barometric pressure or with solar activity.

However, after cycling to nitrogen temperature, bursts of counts were obtained from the counter -- typically on the order of 20 counts per burst emerging over a period of 60 microseconds. One set of data was presented on counts obtained by cycling to nitrogen temperature, showing neutrons essentially only in these bursts.

A totally different type of neutron emission was also claimed by the Frascati group [DeN] following warming from nitrogen temperature over one weekend. A bell-shaped curve rising to a peak of 300 neutrons per ten-minute counting interval extended over some 5 hours. This, of course, is an important experimental result, and provoked great effort toward verification both at Frascati and elsewhere. A recent private communication from M. Martone at Frascati indicates that there has been no confirmation of either the burst results or of the continuous neutron emission from the D-Ti system or from any other dry fusion activity at Frascati. In addition, electrochemical cells operated without producing observable numbers of neutrons, and their operation was terminated during the month of July.

A group at LANL [Me] has conducted dry fusion work with Ti and Pd, and has presented results both at the Santa Fe meeting and in a preprint. This group at LANL uses high-efficiency systems that moderate any fast neutrons emitted from experimental cells, detecting the moderated thermal neutrons in ^3He gas counters. Bursts of neutron counts are sometimes observed 3000-5000 seconds after the sample is removed from liquid nitrogen, at a time when the sample temperature is typically -30 C. These bursts, consisting of about 100 neutrons at most, are seen in about 30% of the samples tested. An attempt to reproduce this effect at Sandia National Laboratory yielded entirely negative results [Ald].

At the Santa Fe workshop, Moshe Gai of Yale presented results obtained in collaboration with Brookhaven National Laboratory, in which no neutrons were detected from electrolytic cells [Ga].

Finally, a conference report from the Bhabha Atomic Research Center (BARC), [Iy] provides text and tabulated results from several groups at BARC. Fig. 1 of the BARC report shows counts from neutron detectors observing a large electrolytic cells, with an estimated 2×10^7 neutrons in the 5 minutes following an overpower trip of the electrolyzer. Tritium and neutrons are observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd. Fig. 2 of the BARC report shows dry fusion ^3He counter output during gradual rise of temperature of 20 g of Ti while deuterium gas was being pumped off. It is also commented that samples could be loaded with deuterium gas at 1 bar and 900 C, and that "one such disc shaped button loaded on Friday 16th June began emitting neutrons on its own, almost 50 hours after loading. It produced (about) 10^6 neutrons over a 85-minute active phase. The background neutron counter did not show any increase in counts over this time."

IIIe. Secondary Neutron Production.

There are severe problems of consistency between the number of tritium atoms found in some of the experiments discussed above and the number of neutrons detected. The BARC abstract reads, "The total quantity of tritium generated corresponds to about 10^{16} atoms suggesting a neutron to tritium branching ratio less than 10^{-8} in cold fusion." But, as discussed above there must be at least

one neutron per 100,000 tritons if the observed tritium were originating from fusion, 1000 times more than was observed!

IV. CHARGED PARTICLES AND GAMMAS

A few experiments [Po, Pr, Re, Su] to measure the 3 MeV protons and/or the 1 MeV tritons produced in the reaction, $D + D \rightarrow {}^3H + p$, have been reported; they are summarized in Table II below. A variety of different methods has been used, but the lowest limit on charged-particle production appears to be that set by Price using plastic track detectors. Their setup was designed so that the light water control cell matched the heavy water cell as closely as possible. Electrolysis was performed for 13 days, and the cathode stoichiometry was determined to be $Pd(H,D)0.8$. Both cells showed track production rates that agreed and were consistent with the alpha-particle emission rate for native Pd foils due to trace (ppm) impurities of the natural ^{238}U and ^{232}Th decay chains; however, no tracks due to protons with energies between 0.2 and 3 MeV or tritons with energies between 0.2 and 1 MeV were found. From these data Price [Pr] set limits on the fusion rate of less than 0.002 per cm^3 per second. This value results in an upper limit of 8.3×10^{-26} fusions per dd pair per second. This is about an order of magnitude lower than the limits obtained using Si surface barrier (SSB) techniques.

(3 cm)

A limit on the fusion rate of 0.028 per cm^3 per second or 1.2×10^{-24} fusions per dd pair per second was obtained by Ziegler [Zi] using a SSB technique. Porter [Po] used a SSB detector to view the back of a 76 micron thick Pd foil cathode in a heavy water electrolysis cell. They obtained a limit of less than 6×10^{-25} protons per dd pair per sec at the 2 sigma level; chemical analysis of their electrolytes showed no evidence for anomalous increases in tritium concentrations. Sundqvist et al. [Su] also used a SSB technique to detect protons. The detector was placed close to Pd foil cathodes that were thin enough to allow all the protons produced to escape from the foil. All of their runs gave a null result within the statistical errors, resulting in a fusion rate of $-2.1 (\pm 2.2) \times 10^{-24}$, if a bulk process is assumed.

Recently, Rehm [Re] has reported using a proportional counter to search for charged particles from electrolytic cells with Pd and Pt electrodes in 0.1 M LiOD in D_2O . They obtained an upper limit of 4×10^{-23} fusions per dd pair per second, not as low as the limits using the other methods.

X In summary, a variety of experimental techniques has been used in searches for charged particles; all of them set very low limits on fusion occurring via the $D + D \rightarrow {}^3H + p$. Most of these results set limits that are considerably less than Jones' [Jo] value of $1.00 (\pm 0.82) \times 10^{-23}$ fusions per dd pair per second for the $D + D \rightarrow {}^3He + n$ channel obtained from neutron measurements. (The uncertainty was calculated by [Su]). *sp*

The upper limit of Price [Pr] of 8×10^{-26} fusions per dd pair per second is much below the average low rate inferred from the neutron measurements of Jones or even those of Menlove [Me]. The extremely low limits which the searches for charged particles (either protons or tritons) place on their production is clearly inconsistent with the reported production of tritium via the cold fusion reaction.

IVa. GAMMA-RAY SEARCHES

As was mentioned above, a rare branch of the D + D reaction proceeds through capture, in which a 23 MeV gamma ray is emitted. Similarly, the p + D reaction is associated with a 5.49 MeV gamma ray. Several searches have been published in which no gamma rays that would be associated with the D + D or p + D capture reactions were seen. They include a report by Henderson [He] who cites limits around $10^{-23}/\text{sec}$ 23 MeV gamma rays emitted per deuteron in various cells. Porter [Po] reports no 5.5 MeV gamma rays -- though no absolute limit is quoted. They also comment on the absence of Pd K X-ray production. Greenwood [Gr] also report limits of 10^{-23} for gamma rays above 1.9 MeV. Other negative results are quoted in the Santa Fe abstracts without quantitative detail.

V. TRITIUM

As discussed above, one branch of the D + D reaction produces tritons and protons. As was also discussed, searches involving the direct detection of charged particles have yielded rather stringent negative results; so have the lack of neutrons. A number of searches have also been made for the tritium accumulated during the electrolysis of D₂O with palladium cathodes, determining tritium content by detecting the radioactive decay of tritium. In such experiments it is important to determine the initial tritium content of the heavy water and recognize the fact that the electrolysis of the heavy water will enrich the naturally occurring tritium in the heavy water.

The detection of tritium by measurement of its beta decay is inherently a less sensitive probe of the D + D reaction than the direct measurement of neutron production or charged particle production. About 10^7 tritium atoms give 1 decay by beta emission per minute. The tritium content of normal water is about 10^{-18} relative to hydrogen but, as discussed in Appendix B the normal manufacturing of heavy water also enriches in tritium and thus heavy water currently being sold gives between 120 and 180 disintegrations per minute (dpm) from tritium decay.

Va. Null Experiments.

Most of the work reported to date on the search for excess tritium produced in electrolytic cells can be accounted for by the electrolytic enrichment process. This includes the original report by Fleischmann and Pons [Fle], and experiments at ANL,[Gre,Red] BNL,[Da,McB,Wi2] Cal Tech,[Le2] CRNL,[Sc] INEL,[Lo] LLNL,[Al] NRL,[Er] ORNL,[Fu,Sc] Sandia,[Na] SRL,[Ra] Texas A & M,[Ma] and Utah.[Wad]

Vb. Tritium Bursts.

A small number of experimenters report occasional irreproducible amounts of excess tritium in their D₂O samples taken from their electrolytic cells after days of operation. This includes observations by Storms[St] at Los Alamos, and Fuller [Fu] and Scott[Sc] at ORNL. The ORNL experiments show single cases of an excess of tritium which is of short duration, after which a cell returns to background level. Storms reports excess tritium, 100 times background, in two cells out of fifty.

Vc. Closed Cells - Correlation with Excess Heat.

Four different groups [McB, McC, Sc, Ma] have now looked for tritium production in closed electrolytic cells. These experiments detect all the tritium from the electrolytic process with the exception of that which may be contained in the Pd cathode. In general, the deuterium inventory in the cathode is negligible compared with the D₂O. Only that tritium formed within the cathode and which remains there because of slow diffusion is unaccounted for. There is no electrolytic enrichment of the tritium in the make up D₂O. In these experiments the total amount of excess tritium formed in the total D₂O is less than 10⁴ T atoms/sec. If this tritium is produced by the D + D reaction, then the maximum amount of excess power (cold fusion power) is 10⁻⁵ milliwatts. In one experiment [Wad] in an open cell there was a heat burst of 35 watts for 90 minutes (187,000 joules). The tritium was measured after the burst and no excess above the electrolytic enrichment was found. Clearly the heat burst does not come from the D + D reaction.

Vd. High Levels of Tritium.

Two groups [Pa, Iy] find tritium at levels of 10¹² to 10¹⁴ T atoms/ml D₂O after periods of electrolysis of the order of hours. This amount of tritium cannot be produced by electrochemical enrichment with the D₂O volume reductions reported. The results of the Bockris [Pa] group at Texas A & M for cells in which excess tritium was found are given in Table 1 of their paper. Excess tritium is not found in all of their cells. A listing of cells in which no excess tritium was found is given in their Table 4. The Bockris cells are 0.1 M in LiOD and have nickel anodes. They precipitate nickel oxide during the electrolysis; some nickel is also electroplated out on the palladium cathode. In one experiment, A8, the specific activity of the D₂ gas produced by the electrolysis was measured. It is 100 times that of the electrolyte.

D₂ (gas) containing tracer amounts of tritium and in equilibrium with D₂O (liquid) has a specific activity that is lower by 0.6 than the D₂O (liquid). If the tritium is formed during electrolysis, this result suggests that it is formed in the chemical species DT and that the tritium in the liquid D₂O is the result of hot atom processes or slow isotopic exchange of the DT (gas) with D₂O (liquid) [Bi2].

~~Wolf~~ [Wo] at Texas A & M have looked for neutron production in Bockris type cells. An upper limit to their neutron production rate is 1 neutron/second, which is 10⁻¹⁰ times that of the tritium production rates reported with similar cells by Packham et al. [Pa]. This is a large discrepancy from the equal production rates for neutrons and tritons required by the branching ratio in the fusion reaction, discussed in section II, and is inconsistent, by a factor of 10,000 to 100,000, even with the secondary neutrons that must accompany the tritons produced from nuclear fusion. One is strongly inclined to conclude that the excess tritium found in the electrochemical cells cannot be the result of nuclear fusion in the cell.

The most extensive and systematic search for tritium in the electrolysis of D₂O with Pd cathodes has been carried out by Martin [Ma] at Texas A & M. He has used both open and closed cells. His cathodes come from either Johnson & Matthey, a major supplier, or Hoover and Strong, who supplied the cathodes to the Bockris [Pa] group. He has operated cells with Pt, Ni wire and Ni gauze

(obtained from Bockris) anodes. In none of his cells does he find any excess tritium beyond that expected from electrolytic enrichment. Nor does he find any neutrons. Two of his cells produced excess heat but no tritium. In short, he has been unable to reproduce the results of the Bockris group.

The BARC [Iy] group have found amounts of tritium comparable to the Bockris group in the D₂O electrolyte from cells in which electrolysis was carried out for a few days with currents varying between 1 to 100 amperes. As was already mentioned above, here there is again a factor of 1000 internal inconsistency between their measured neutron yields and the neutrons that have to be there if this tritium was indeed produced by fusion -- even if one assumes the very unlikely drastic modification of the branching ratio in the D + D reaction.

The experiments carried out to date include the large number of null experiments. There are a few experiments in which excess tritium is found, and which other groups have not been able to reproduce. These measurements also contain a serious internal inconsistency, in that the ratio of measured neutrons to tritium is smaller by orders of magnitude than what is consistent with a fusion process being their source. Additional investigations are desirable to clarify the origin of the excess tritium that is occasionally observed.

VI. EXOTIC EXPLANATIONS

The data on fusion products, even where positive results are reported, give rates far below those that would be expected from the levels of heat reported in some electrolysis experiments. There have been some attempts to propose mechanisms where the reaction heat from the D + D → ⁴He process would go entirely into lattice heat, rather than a photon [Wal, Ha]. Analogies have been made with the internal conversion process, and with the Mossbauer effect. Neither of these analogies is applicable to ⁴He.

Internal conversion allows an atomic electron of an excited nucleus to carry off the reaction instead of a photon. This process is understood quantitatively -- it is dominant in heavy atoms with tightly bound inner electrons and for low energy (less than 1 MeV) photons. In helium the atomic electrons are loosely bound and the photon is 23.8 MeV -- there can not be any appreciable coupling between the photon and the atomic electrons, and internal conversion or any related process cannot take place at anywhere near the rate that would be required.

In the Mossbauer effect the momentum of a very low energy (below 100 keV) photon is taken up by the entire tattice in a coherent mode, but not its energy. The process cannnot be relevant to the present process.

Considering experimental evidence more generally, there have been careful studies of a very large number of reactions analogous to the D + D fusion process, in which gamma rays of comparable energy emitted from low-energy nuclear reactions (thermal-neutron capture gamma rays) and the cross sections for capture have been studied very carefully and quantitatively. Their knowledge is essential to the operation of fission reactors. If there were any anomalous processes in which the energy of a capture gamma ray were converted into lattice heat, this would have almost certainly been noticed as a discrepancy in cross sections with major implications for the operation of reactors. After four decades of extensive study of the processes relevant to

the operation of fission reactors the possibility is extremely remote that an entirely new process, that could dominate these nuclear reactions, would have remained hidden.

VII. SEARCH FOR PRODUCTS OF COLD FUSION IN THE EARTH

Products of low-level cold fusion have been inferred to be produced by natural geologic processes [Jo, Jo1]. The $^3\text{He} : ^4\text{He}$ ratio is anomalously high in volatiles from deep-source volcanoes such as Hawaii, Iceland, and Yellowstone [Cr, Ku, Mam]; anomalous ^3H is also suggested by fragmentary data [Om, Jo2], and production of other radiogenic products such as ^{36}Cl have been predicted [Pk]. Although the high ^3He values have previously been considered relict from early earth processes, presence of anomalous ^3H or ^{36}Cl (beyond that due to bomb tests) would be definitive evidence of natural cold fusion at depth within the earth. Implications would be major for geophysical problems such as heat-flow modelling, element-distribution with depth, and composition of the Earth's core.

Although some knowledgeable isotope geochemists see no evidence for naturally occurring cold fusion [Cr1], several government and university labs are searching for evidence of such fusion processes as recorded by volcanic volatiles [Jo2, Ky, Go, Loc, Qu]. Even if laboratory experiments for cold fusion are discredited, such geologic studies could add much to understanding of the behavior of volcanic volatiles. No rigorous results are yet available, but experiments proposed or underway at Brigham Young, Los Alamos, Lawrence Livermore, New Mexico Tech, and the U.S. Geological Survey (Denver) should yield data within 6 months to 1 year.

VIII. SUMMARY

A number of careful experiments have been carried out to search for the expected products of cold fusion. None have seen these products at anywhere near the level that would be expected from the heat production reported in electrolysis, by many orders of magnitude. Some experiments report neutrons or tritium at a much lower level -- however, the rates of these two fusion products (measured in the same experiments) are inconsistent with each other, again by large factors.

The neutron bursts reported in some experiments also suffer from not being reproducible by other experimenters. While it is conceivable that some mechanism might produce very small bursts of hot fusion (e.g. high voltage internal sparks associated with fracture of the material at certain temperatures), at the present time the experimental evidence is not readily reproducible, and if real, the phenomenon does not appear to be related to "cold fusion" as postulated in the heat production experiments.

If there were such a process ^{such} as room temperature fusion, it would require not only

- (a) the circumvention of fundamental quantum mechanical principles, which have been carefully tested against numerous measurements of barrier penetration (such as the systematics of spontaneous fission and alpha radioactivity lifetimes and those of nuclear cross sections), but also

- (b) drastic modifications of branching ratios in the D + D reaction, and
- (c) the invention of an entirely new nuclear reaction process.

A quotation from Lewis Carroll seems appropriate:

'Alice laughed. "There's no use trying," she said: "one can't believe impossible things."

"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

good for
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TABLE I. SOME COLD FUSION NEUTRON RATES

Authors	Reference	Neutrons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
Yield corresponding to 1 watt of heat production [Fle]		3×10^{-11}	3×10^{12}
Yield corresponding to neutron yield of Jones et al [Jo]		10^{-23}	1
Broer et al [Br]		$< 2.2 \times 10^{-24}$	< 0.2
Williams et al [Wi]			< 0.2
Lewis et al [Le]		$< 1.5 \times 10^{-24}$	$< .15$
Alber et al [Alb]		$< 5 \times 10^{-25}$	< 0.05
Gai et al [Ga]		$< 2 \times 10^{-25}$	< 0.02
Schriber et al [Schr]			< 0.02
Kashy et al [Ka]		10^{-25}	< 0.01
De Clais et al [DeCl]			$\lesssim 0.01$ $\lesssim 0.001$

[a] assuming that neutrons are produced throughout the volume.

TABLE II. SOME COLD FUSION FAST CHARGED PARTICLE RATES

Authors	Reference	Protons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
Yield corresponding to 1 watt of heat production [Fle]		3×10^{-12}	3×10^{12}
Jones et al.	[Jo]	1×10^{-23}	1.0
Rehm et al.	[Reh]	$< 4 \times 10^{-23}$	< 4
Schrieder et al.	[Schr]	$< 3.1 \times 10^{-24}$	< 0.31 [b]
Sundquist et al.	[Su]	$< 2 \times 10^{-24}$	< 0.2
Ziegler et al.	[Zi]	$< 1.2 \times 10^{-24}$	< 0.12 [b]
Porter et al.	[Po]	$< 6.7 \times 10^{-25}$	< 0.07
Price et al.	[Pr]	$< 8.3 \times 10^{-26}$	< 0.008

[a] assuming that particles are produced throughout the volume.

[b] 6. Rehm et al comment that the choice of the low-energy cutoff (e.g. 1 MeV in Ref. [Zi]) restricts the emission angle of the protons with respect to the foil to a small cone representing only a few of the total solid angle. This effect seems to have been neglected in the efficiency calculations for the limits quoted by these authors.

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APPENDIX A

NEUTRON DETECTION.

Neutrons from dd fusion can be detected either at their initial energy in the MeV range as "fast" neutrons, or their energy has been "moderated" by sharing it in successive collisions with light material -- particularly hydrogen. Fast neutrons can be detected by photomultiplier tubes viewing the proton recoil in plastic or liquid scintillation material. Slow neutrons (those that have lost almost all their kinetic energy and are in thermal equilibrium at room temperature) are conventionally detected by the charged particles produced when the neutron is captured with high probability in the nucleus of an atom of ^{10}B (producing an alpha particle), or in a ^3He nucleus, producing a recoil proton. A noble gas, ^3He is used in the form of a proportional counter, while boron can be used either in the form of BF_3 proportional counters or in the solid form, with the boron immersed in plastic or inorganic scintillator viewed by a photomultiplier.

Additionally, neutrons can be detected after moderation by their capture in some material of very high capture cross section (such as cadmium Cd), which produces several gamma rays that may, in turn, be detected by a photomultiplier viewing a scintillation detector. Similarly, neutrons moderated in water are almost entirely captured on the protons ("radiative capture"), giving rise to a deuteron plus a gamma ray with 2.2 MeV.

Finally, moderated neutrons may be captured in a trace element in the moderator (silver is a detector of choice) to produce a radioactive material that can be transported away from the experimental apparatus and counted separately with high efficiency at low background. The emitted radiation is typically a beta ray (negative electron), or a characteristic gamma ray following the beta decay. Of course, the world has enormous experience since the 1930s in detecting neutrons and in detecting neutrons from the D + D fusion reaction.

APPENDIX B

CONSIDERATIONS IN TRITIUM CONCENTRATIONS.

Tritium is produced in the atmosphere by cosmic ray bombardment. Most of such tritium ends up in the oceans and in rivers. The "natural" abundance of tritium varies widely and was greatly increased by atmospheric testing of thermonuclear weapons in the '50s and in the early '60s. The order of magnitude of tritium in ordinary water is $\text{T/H} - 10^{-18}$ (1 TU). Sources vary from 1 to 200 TU. The production of heavy water from ordinary water is even more efficient in the enrichment of tritium than deuterium from the feed material. Most of the heavy water currently available is produced by the $\text{H}_2\text{S} - \text{H}_2\text{O}$ dual temperature exchange process (GS process). The tritium content of fresh heavy water produced by the GS process is 68 dpm/ml D_2O /TU feed. Processes that are more efficient than the GS process in heavy isotope enrichment will have a minimum tritium specific activity of 50 dpm/ml D_2O /TU feed. Heavy water currently being sold on the open market has a specific activity in the range 120 - 180 dpm/ml D_2O . There are sources of D_2O with specific activity as high as 10^4 dpm/ml.

Most of the work done to date on the search for tritium produced in the electrolysis of D₂O in cells with palladium cathodes has been done in open cells. The measurements are frequently limited to assays of the specific activities of the starting D₂O and the electrolyte after electrolysis. In general, there have been periodic additions of D₂O to replace the D₂O decomposed to form palladium hydride and D₂(gas). To determine how much tritium, if any, has been produced requires a complete inventory of the tritium at the beginning and end of the experiment. From the data on the current and on the duration of the electrolysis it is possible to estimate the amount of D₂O which has been electrolyzed. Electrolysis will enrich the tritium in the D₂O of an electrolytic cell. The amount of enrichment is primarily a function of the amount of water electrolyzed for a given type of cathode. It can reach a factor of 5 when 95% of the initial charge of water is electrolyzed. Thus a careful analysis of an electrolytic experiment must be carried out if one is to interpret specific activities of tritium after electrolysis, below 1000 dpm/ml of D₂O, as anything other than electrolytic enrichment [Bi].

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etc.
Draft - Oct. 10, 1989
Nate Lynn

FUSION PRODUCTS

I. INTRODUCTION

The nuclear fusion of deuterium has been studied intensively for over 40 years. The reaction between two low energy deuterium nuclei can proceed in three ways:

- (a) $D + D \rightarrow {}^3He + n + 3.269 \text{ MeV}$
- (b) $D + D \rightarrow {}^3H + p + 4.037 \text{ MeV}$
- (c) $D + D \rightarrow {}^4He + \text{gamma} (23.847 \text{ MeV})$

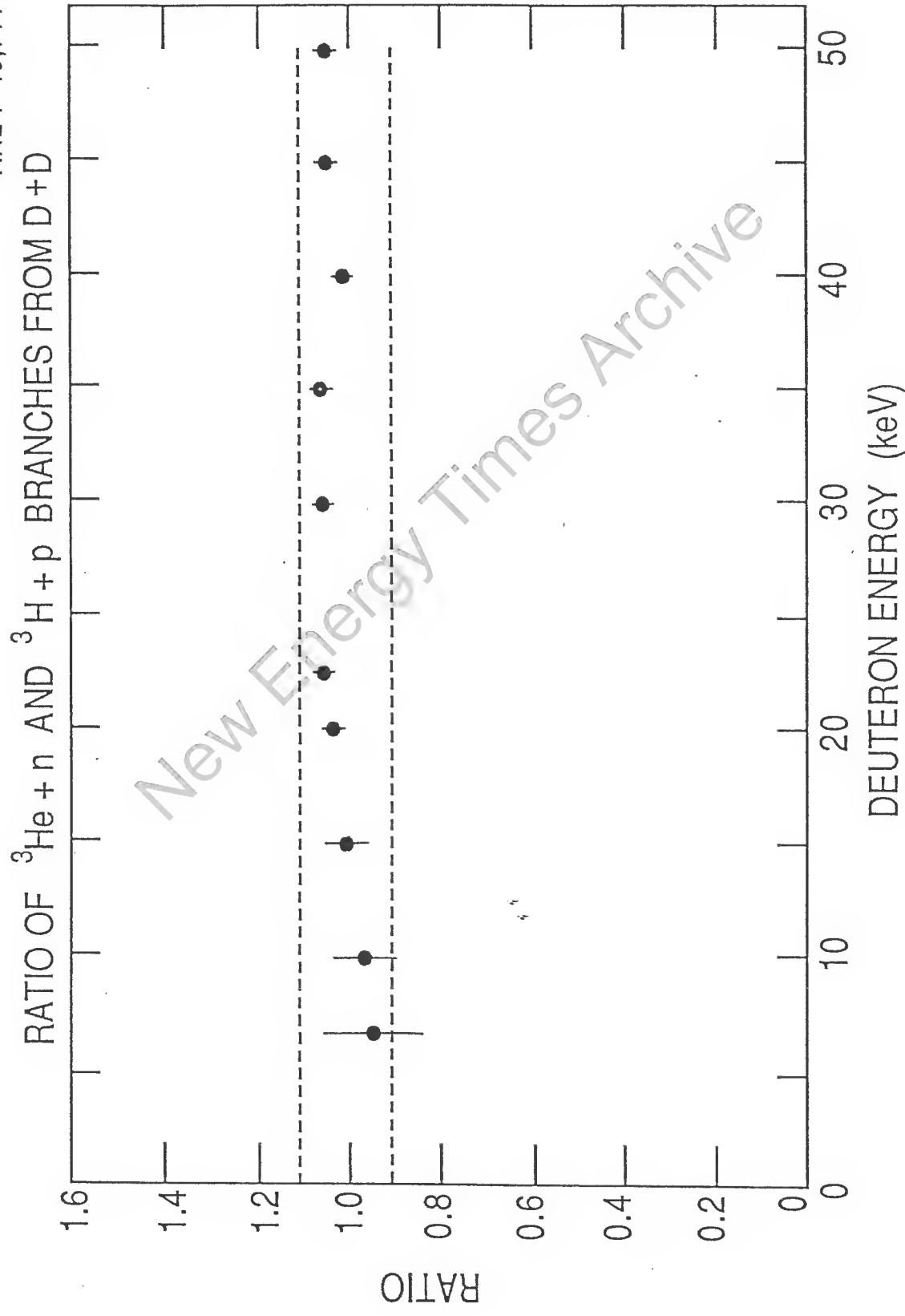
The reactions (a) and (b) have been studied down to deuteron energies of a few keV and the cross sections found to be equal to within 10%. In the interaction of deuteron beams with heavy ice or metal deuteride targets, almost one 2.45 MeV neutron is produced (with an accompanying 3He) for every triton (with an accompanying proton). This near-equality of neutron and proton branches of the $D + D$ reaction, shown in figure 1, is a reflection of the basic symmetry of nuclear forces between proton and neutron, disturbed only slightly at the MeV energies of the emerging particles by the Coulomb interaction, which is not symmetrical between proton and neutron. The cross sections for reaction (c) are very small -- on the order of 10^7 lower than the first two.

All nuclear reactions at low energies between two deuterons are retarded by the Coulomb repulsion between the positively charged nuclei -- the penetration of the repulsive Coulomb barrier changes exponentially with bombarding energy: for instance the measured cross section for reaction (b) changes from 0.2 microbarns at 2.7 keV to 35 millibarns at 100 keV. But the ratios for the three reactions appear to be constant below 100 keV.

Any fusion between deuterium nuclei must lead to detectable fusion products. For reaction (a) neutrons are the most easily detected product, by direct counting. For (b) the protons or tritons can be detected by direct counting, and the accumulated tritium could also be identified by its radioactivity, albeit with lower sensitivity. Neutron counting is perhaps again the most useful technique here, since neutrons must be produced by the energetic tritons interacting with other deuterons in the material at the rate of 1 neutron for every 10,000 to 50,000 tritons. Reaction (c) leads to readily detectable high energy gamma rays and 4He ; the latter may be identified by mass spectroscopic measurements, whose sensitivity is low -- though the 10^{17} levels implied by 1 watt of heat should be readily observable.

In the following we summarize the experimental evidence on these fusion products. First we discuss the plausibility of reactions at room temperature and the issue of whether the constancy of the three reaction modes is a reasonable extrapolation to very low energies. Then the data on neutrons, charged particles, gamma rays and tritium are summarized. Finally, some comments are included on the more exotic explanations, and geophysical evidence is summarized on proposed cold fusion in the interior of the earth.

ANL-P-19,711



II. THE REACTION PROCESS

Fusion reactions can occur only if during a nuclear collision the Coulomb barrier is surmounted or, at low energies, penetrated so that the nuclei approach each other within about 10^{-12} cm. This distance is some 10000 times smaller than the typical separations of atoms in ordinary matter. The penetration of the barrier at low energies takes place through a well-understood quantum mechanical phenomenon called tunneling that allows fusion to occur in collisions far less violent than might be required otherwise.

In the thermonuclear fusion that occurs in stars and in laboratory "hot fusion" experiments, very high temperatures provide the violent collisions required to produce fusion. However, in the so-called cold fusion experiments, it is claimed that the penetration of the barrier through quantum mechanical tunneling has somehow become so effective as to allow fusion to occur even at room temperatures. Further, some of the experimenters claim that the nuclear process is changed by some unspecified mechanism so as to alter dramatically the nature of the reaction products. Each of these claims must be understood as separate and equally surprising.

Some simple calculations serve to illustrate how remarkable the claim of fusion at room temperatures really is. The fusion rate for the two deuterium nuclei in a deuterium molecule (where they are even closer than they are when embedded in a metal) results in one fusion per year in a solar mass of deuterium. Further, the fusion of protons and deuterons is 10^9 times faster than the D + D reaction claimed to have been observed (although it is still extraordinarily slow). There is no known mechanism by which these rates could be enhanced by the 40-50 orders of magnitude required to agree with the reported observations.

One commonly invoked mechanism for enhancing cold fusion rates is screening by "heavy" electrons. It is true that endowing the electron with a hypothetical mass some 5-10 times larger than it actually has would enhance fusion rates sufficiently to agree with most cold fusion claims [Ko]. It is also true that there are "heavy fermion" materials whose thermodynamic properties at very low temperatures are characteristic of quasiparticles with masses many times those of a free electron. However, this phenomenon is understood as involving long-wavelength excitations in which strong correlations "dress" electrons near the fermi surface. As such, heavy fermions extend over many lattice sites. Because the tunnelling in nuclear fusion occurs at distances smaller than one lattice site, only the short-wavelength "bare" electron excitations are relevant for screening, and cannot enhance the fusion rate significantly.

IIa. The D + D Branching Ratios.

The relative rates of reactions (a), (b), and (c) are called the branching ratios and are a crucial issue in the discussion of some cold fusion claims. These reactions have been studied in laboratory experiments using accelerators for deuteron energies above a few keV [Kr]; the smallness of both cross sections prevents reliable measurements at lower energies. The ratio between the two rates exhibits a weak energy dependence and is near 1.0 at the lowest energies as seen in figure 1. Data from muon-catalyzed D + D fusion [Bal], which probes an even lower energy range, is still consistent with nearly equal rates.

A branching ratio of more than one million would be required to explain experiments that claim to observe high fusion rates (either through heat or tritium production) without a corresponding high neutron flux. As "cold fusion" is thought to occur at energies on the order of eV, this is not directly ruled out by the data discussed above. However, there is no known mechanism for inducing such a rapid energy-dependence in the branching ratio. The Oppenheimer-Phillips process involving the Coulomb break-up of the deuteron has sometimes been invoked in this regard. However, this approximation is not valid at low energies in the D + D system.

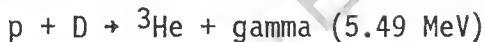
IIb. The Gamma Branch.

Some researchers have hypothesized that the $D + D \rightarrow {}^4He + \gamma$ (23.847 MeV) reaction, which is ordinarily some 10^7 times weaker [Bar] than reactions (a) and (b) in which two fragments are produced, somehow dominates in cold fusion situations. To be consistent with the lack of neutrons, a very large enhancement of the gamma branch by a factor somewhere in excess of 10^{13} would be required. We know of no way whereby the atomic or chemical environment can effect such an enhancement, as this ratio is set by phenomena on a length scale some 10^4 times smaller than the atomic scale.

Even if there were such an enhancement, the absence of observed high-energy electromagnetic radiation (photons, positrons, or fast electrons) rules out such a mechanism. While direct coupling to the lattice through unspecified mechanisms has been invoked to suppress such radiation, any such coupling must occur through the electromagnetic field and would result in some observable high-energy radiation.

IIc. The p + D Reaction.

It has been suggested that an alternative fusion process could be the reaction



for which the penetration factors are still overwhelmingly small at room temperature, but somewhat less so than for the D + D process [Ko]. This reaction must produce a readily observable gamma ray and if it is to account for 1 watt of heat, then it should also produce 3He in observable concentrations.

IID. Estimate of Secondary Yields from Fusion Products.

i) **Neutrons from tritium.** The tritons produced in reaction (b) are produced with an energy of 1.01 MeV. This energy must be lost in the immediately surrounding material, which in the case of an electrolytic cell is either the Pd electrode saturated with deuterium, or heavy water. The tritons will therefore bombard the deuterium in the surrounding material. The t+d reaction is a rich source of neutrons, with a cross section that reaches 5 barns at 0.12 MeV, then falls to about 0.7 barns at 0.5 MeV, and reaches slightly below 0.3 barns at 1 MeV. For the 1.01 MeV tritons from the D + D reaction one may assume an average cross section of about 1.2 barns. For tritons that are stopped in PdD this translates into a neutron yield between 0.15 and 0.2×10^{-4} neutrons per triton;

2×10^{-5}

9x5-5

for tritons stopping in heavy water there are about 0.9×10^{-4} per triton.

ii) Coulomb excitation of Pd by protons. The even Pd isotopes (104, 106, 108, 110) with abundances of 11, 27, 26, 12 % have first-excited 2^+ states at 555, 512, 434, 374 keV and $B(E2)$ values between 0.5 and 0.8 barns. The cross sections for Coulomb excitation are in the vicinity of 20 to 50 mb and thus the yields expected are 2 to 5×10^{-6} per proton. In palladium the half thickness for absorption of these gamma rays is about 4 mm, in water it is several cm.

In terms of power, there must be about 10^8 /sec secondary neutrons per watt of fusion, even if direct neutron production is completely suppressed and all the reaction goes into tritium production. Under these conditions there must also be slightly under 10^7 secondary photons per second, of well defined energies, in the 500 keV range.

III. NEUTRONS

IIIa. Detection.

As discussed above neutrons are a major product of D + D fusion. Neutrons are very convenient particles to detect, since they interact only with the nuclei of atoms and so can emerge from reaction vessels of substantial size unscathed and without having lost any energy. Similarly, large counters can be used without the problem of thin entrance windows, since neutrons enter into the volume of the counter without difficulty. Some simple facts about neutron detection are summarized in Appendix A.

IIIb. Selection of Data.

In what follows, we have tried to use published material, where available, or material prepared for publication and presented at formal meetings or as preprints distributed without restriction as to citation. It is important to include not only positive results, that claim the detection of neutrons, but also the negative ones, that have attempted to replicate the experimental procedure of the former and failed to detect neutrons at a level of sensitivity substantially better than the positive results.

IIIc. Initial claims.

The University of Utah (UU) group in its initial publication [Fle] claimed the detection of neutrons from D + D by virtue of the gamma ray emitted by the capture of the moderated neutron in the water bath surrounding the electrolytic cells. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper, considerably narrower than is possible with this type of detector, and with internal inconsistencies in the energy scale.

These very questions were taken up by a group at MIT, [Pe] who showed that the photo peak at 2.2 MeV obtained at MIT from Cf spontaneous fission neutrons moderated in water and radiatively captured on protons is accompanied by other peaks from natural background that enable one to calibrate the energy, and

successive interchange between UU and MIT groups in the scientific literature has demonstrated that the claimed detection of neutrons by the proton capture gamma ray at UU was an artifact of the experimental apparatus.

The original publication from Brigham Young University (BYU) [Jo] presented the detection of neutrons as the sole experimental evidence for the existence of cold nuclear fusion. The neutrons were detected in a two-stage neutron counter -- first by the proton recoil in organic scintillator, followed within a few tens of microseconds by a signal from the capture of the moderated neutron on boron viewed by the same photomultipliers. This double detection of a single neutron serves substantially to reduce the ambient background due to gamma rays, although there remains background in the experiment due to gamma rays and to real neutrons from cosmic rays* and other sources. The group at BYU has chosen to attempt to vary the experimental conditions in order to obtain a greater rate of D + D fusion, and so has not presented much more data than the original paper on the detection of neutrons with that counter. In fact, BYU has been working in collaboration with other groups, notably at LANL [Me], and also with a group at Yale University. The original claim of neutron detection five standard deviations above the background is somewhat reduced in statistical strength if one considers the degrees of freedom that are fixed by the presentation of a peak in one of a number of experiments and at a particular energy, and also the possible fluctuation in the cosmic-ray neutron background. Ordinarily, however, such a result can be improved through improved shielding or by moving to an underground site.

Typical of the latter is work presented by the group at Sandia National Laboratory, [Ald] in which a site was found with substantially less background and results presented for a limit on neutrons produced in electrolytic fusion. Similar results from the Frejus tunnel in France were also presented in Santa Fe. [DeC1]

Many claims have been made for the production and detection of neutrons produced in electrochemical cells, but these claims have almost all been withdrawn or moderated by the discovery of difficulties with the counter -- particularly with the BF₃ counters used. In some cases, the counters are sensitive to humidity; in others to microphonic noise (vibration); or to other afflictions. A summary of some of the limits on neutron fluxes reported, compared to the flux reported by the BYU group, is shown in Table I.

IIId. Dry Fusion.

Results presented in April 1989 by a group at Frascati [DeN] opened an entirely new opportunity for the observation of D + D cold nuclear fusion. In this work, deuterium gas at 60 atmospheres pressure (60 bar) was allowed to contact titanium lathe turnings in a stainless steel reaction vessel. That allowed the temperature of the sample to be varied either by heating or by cooling. No neutrons were observed from the hydriding reaction at room temperature or at elevated temperature, when viewed by a nearby BF₃ counter.

*Additional care is needed as the rate of cosmic ray neutrons can fluctuate by 20% or more with variations in barometric pressure or with solar activity.

However, after cycling to nitrogen temperature, bursts of counts were obtained from the counter -- typically on the order of 20 counts per burst emerging over a period of 60 microseconds. One set of data was presented on counts obtained by cycling to nitrogen temperature, showing neutrons essentially only in these bursts.

A totally different type of neutron emission was also claimed by the Frascati group [DeN] following warming from nitrogen temperature over one weekend. A bell-shaped curve rising to a peak of 300 neutrons per ten-minute counting interval extended over some 5 hours. This, of course, is an important experimental result, and provoked great effort toward verification both at Frascati and elsewhere. A recent private communication from M. Martone at Frascati indicates that there has been no confirmation of either the burst results or of the continuous neutron emission from the D-Ti system or from any other dry fusion activity at Frascati. In addition, electrochemical cells operated without producing observable numbers of neutrons, and their operation was terminated during the month of July.

A group at LANL [Me] has conducted dry fusion work with Ti and Pd, and has presented results both at the Santa Fe meeting and in a preprint. This group at LANL uses high-efficiency systems that moderate any fast neutrons emitted from experimental cells, detecting the moderated thermal neutrons in ^3He gas counters. Bursts of neutron counts are sometimes observed 3000-5000 seconds after the sample is removed from liquid nitrogen, at a time when the sample temperature is typically -30 C. These bursts, consisting of about 100 neutrons at most, are seen in about 30% of the samples tested. An attempt to reproduce this effect at Sandia National Laboratory yielded entirely negative results [Ald].

At the Santa Fe workshop, Moshe Gai of Yale presented results obtained in collaboration with Brookhaven National Laboratory, in which no neutrons were detected from electrolytic cells [Ga].

Finally, a conference report from the Bhabha Atomic Research Center (BARC), [Iy] provides text and tabulated results from several groups at BARC. Fig. 1 of the BARC report shows counts from neutron detectors observing a large electrolytic cells, with an estimated 2×10^7 neutrons in the 5 minutes following an overpower trip of the electrolyzer. Tritium and neutrons are observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd. Fig. 2 of the BARC report shows dry fusion ^3He counter output during gradual rise of temperature of 20 g of Ti while deuterium gas was being pumped off. It is also commented that samples could be loaded with deuterium gas at 1 bar and 900 C, and that "one such disc shaped button loaded on Friday 16th June began emitting neutrons on its own, almost 50 hours after loading. It produced (about) 10^6 neutrons over a 85-minute active phase. The background neutron counter did not show any increase in counts over this time."

IIIe. Secondary Neutron Production.

There are severe problems of consistency between the number of tritium atoms found in some of the experiments discussed above and the number of neutrons detected. The BARC abstract reads, "The total quantity of tritium generated corresponds to about 10^{16} atoms suggesting a neutron to tritium branching ratio less than 10^{-8} in cold fusion." But, as discussed above there must be at least

one neutron per 100,000 tritons if the observed tritium were originating from fusion, 1000 times more than was observed!

IV. CHARGED PARTICLES AND GAMMAS

A few experiments [Po, Pr, Re, Su] to measure the 3 MeV protons and/or the 1 MeV tritons produced in the reaction, $D + D \rightarrow {}^3H + p$, have been reported; they are summarized in Table II below. A variety of different methods has been used, but the lowest limit on charged-particle production appears to be that set by Price using plastic track detectors. Their setup was designed so that the light water control cell matched the heavy water cell as closely as possible. Electrolysis was performed for 13 days, and the cathode stoichiometry was determined to be $Pd(H,D)0.8$. Both cells showed track production rates that agreed and were consistent with the alpha-particle emission rate for native Pd foils due to trace (ppm) impurities of the natural ^{238}U and ^{232}Th decay chains; however, no tracks due to protons with energies between 0.2 and 3 MeV or tritons with energies between 0.2 and 1 MeV were found. From these data Price [Pr] set limits on the fusion rate of less than 0.002 per cm^3 per second. This value results in an upper limit of 8.3×10^{-26} fusions per dd pair per second. This is about an order of magnitude lower than the limits obtained using Si surface barrier (SSB) techniques.

A limit on the fusion rate of 0.028 per cm^3 per second or 1.2×10^{-24} fusions per dd pair per second was obtained by Ziegler [Zi] using a SSB technique. Porter [Po] used a SSB detector to view the back of a 76 micron thick Pd foil cathode in a heavy water electrolysis cell. They obtained a limit of less than 6×10^{-25} protons per dd pair per sec at the 2 sigma level; chemical analysis of their electrolytes showed no evidence for anomalous increases in tritium concentrations. Sundqvist et al. [Su] also used a SSB technique to detect protons. The detector was placed close to Pd foil cathodes that were thin enough to allow all the protons produced to escape from the foil. All of their runs gave a null result within the statistical errors, resulting in a fusion rate of $-2.1 (\pm 2.2) \times 10^{-24}$, if a bulk process is assumed.

Recently, Rehm [Re] has reported using a proportional counter to search for charged particles from electrolytic cells with Pd and Pt electrodes in 0.1 M LiOD in D_2O . They obtained an upper limit of 4×10^{-23} fusions per dd pair per second, not as low as the limits using the other methods.

In summary, a variety of experimental techniques has been used in searches for charged particles; all of them set very low limits on fusion occurring via the $D + D \rightarrow {}^3H + p$. Most of these results set limits that are considerably less than Jones' [Jo] value of $1.00 (\pm 0.82) \times 10^{-23}$ fusions per dd pair per second for the $D + D \rightarrow {}^3He + n$ channel obtained from neutron measurements. (The uncertainty was calculated by [Su]).

The upper limit of Price [Pr] of 8×10^{-26} fusions per dd pair per second is much below the average low rate inferred from the neutron measurements of Jones or even those of Menlove [Me]. The extremely low limits which the searches for charged particles (either protons or tritons) place on their production is clearly inconsistent with the reported production of tritium via the cold fusion reaction.

IVa. GAMMA-RAY SEARCHES

As was mentioned above, a rare branch of the D + D reaction proceeds through capture, in which a 23-MeV gamma ray is emitted. Similarly, the p + D reaction is associated with a 5.49-MeV gamma ray. Several searches have been published in which no gamma rays that would be associated with the D + D or p + D capture reactions were seen. They include a report by Henderson [He] who cites limits around $10^{-23}/\text{sec}$ 23-MeV gamma rays emitted per deuteron in various cells. Porter [Po] reports no 5.5-MeV gamma rays -- though no absolute limit is quoted. They also comment on the absence of Pd K X-ray production. Greenwood [Gr] also report limits of 10^{-23} for gamma rays above 1.9 MeV. Other negative results are quoted in the Santa Fe abstracts without quantitative detail.

V. TRITIUM

As discussed above, one branch of the D + D reaction produces tritons and protons. As was also discussed, searches involving the direct detection of charged particles have yielded rather stringent negative results; so have the lack of neutrons. A number of searches have also been made for the tritium accumulated during the electrolysis of D₂O with palladium cathodes, determining tritium content by detecting the radioactive decay of tritium. In such experiments it is important to determine the initial tritium content of the heavy water and recognize the fact that the electrolysis of the heavy water will enrich the naturally occurring tritium in the heavy water.

The detection of tritium by measurement of its beta decay is inherently a less sensitive probe of the D + D reaction than the direct measurement of neutron production or charged particle production. About 10^7 tritium atoms give 1 decay by beta emission per minute. The tritium content of normal water is about 10^{-18} relative to hydrogen but, as discussed in Appendix B the normal manufacturing of heavy water also enriches in tritium and thus heavy water currently being sold gives between 120 and 180 disintegrations per minute (dpm) from tritium decay.

Va. Null Experiments.

Most of the work reported to date on the search for excess tritium produced in electrolytic cells can be accounted for by the electrolytic enrichment process. This includes the original report by Fleischmann and Pons [Fle], and experiments at ANL,[Gre,Red] BNL,[Da,McB,Wi2] Cal Tech,[Le2] CRNL,[Sc] INEL,[Lo] LLNL,[Al] NRL,[Er] ORNL,[Fu,Sc] Sandia,[Na] SRL,[Ra] Texas A & M,[Ma] and Utah.[Wad]

Vb. Tritium Bursts.

A small number of experimenters report occasional irreproducible amounts of excess tritium in their D₂O samples taken from their electrolytic cells after days of operation. This includes observations by Storms[St] at Los Alamos, and Fuller [Fu] and Scott[Sc] at ORNL. The ORNL experiments show single cases of an excess of tritium which is of short duration, after which a cell returns to background level. Storms reports excess tritium, 100 times background, in two cells out of fifty.

Vc. Closed Cells - Correlation with Excess Heat.

Four different groups [McB, McC, Sc, Ma] have now looked for tritium production in closed electrolytic cells. These experiments detect all the tritium from the electrolytic process with the exception of that which may be contained in the Pd cathode. In general, the deuterium inventory in the cathode is negligible compared with the D₂O. Only that tritium formed within the cathode and which remains there because of slow diffusion is unaccounted for. There is no electrolytic enrichment of the tritium in the make up D₂O. In these experiments the total amount of excess tritium formed in the total D₂O is less than 10⁴ T atoms/sec. If this tritium is produced by the D + D reaction, then the maximum amount of excess power (cold fusion power) is 10⁻⁵ milliwatts. In one experiment [Wad] in an open cell there was a heat burst of 35 watts for 90 minutes (187,000 joules). The tritium was measured after the burst and no excess above the electrolytic enrichment was found. Clearly the heat burst does not come from the D + D reaction. b.v

Vd. High Levels of Tritium.

Two groups [Pa, Iy] find tritium at levels of 10¹² to 10¹⁴ T atoms/ml D₂O after periods of electrolysis of the order of hours. This amount of tritium cannot be produced by electrochemical enrichment with the D₂O volume reductions reported. The results of the Bockris [Pa] group at Texas A & M for cells in which excess tritium was found are given in Table 1 of their paper. Excess tritium is not found in all of their cells. A listing of cells in which no excess tritium was found is given in their Table 4. The Bockris cells are 0.1 M in LiOD and have nickel anodes. They precipitate nickel oxide during the electrolysis; some nickel is also electroplated out on the palladium cathode. In one experiment, A8, the specific activity of the D₂ gas produced by the electrolysis was measured. It is 100 times that of the electrolyte.

D₂ (gas) containing tracer amounts of tritium and in equilibrium with D₂O (liquid) has a specific activity that is lower by 0.6 than the D₂O (liquid). If the tritium is formed during electrolysis, this result suggests that it is formed in the chemical species DT and that the tritium in the liquid D₂O is the result of hot atom processes or slow isotopic exchange of the DT (gas) with D₂O (liquid) [Bi2].

Wolf [Wo] at Texas A & M have looked for neutron production in Bockris type cells. An upper limit to their neutron production rate is 1 neutron/second, which is 10⁻¹⁰ times that of the tritium production rates reported with similar cells by Packham et al. [Pa]. This is a large discrepancy from the equal production rates for neutrons and tritons required by the branching ratio in the fusion reaction, discussed in section II, and is inconsistent, by a factor of 10,000 to 100,000, even with the secondary neutrons that must accompany the tritons produced from nuclear fusion. One is strongly inclined to conclude that the excess tritium found in the electrochemical cells cannot be the result of nuclear fusion in the cell.

The most extensive and systematic search for tritium in the electrolysis of D₂O with Pd cathodes has been carried out by Martin [Ma] at Texas A & M. He has used both open and closed cells. His cathodes come from either Johnson & Matthey, a major supplier, or Hoover and Strong, who supplied the cathodes to the Bockris [Pa] group. He has operated cells with Pt, Ni wire and Ni gauze

(obtained from Bockris) anodes. In none of his cells does he find any excess tritium beyond that expected from electrolytic enrichment. Nor does he find any neutrons. Two of his cells produced excess heat but no tritium. In short, he has been unable to reproduce the results of the Bockris group.

The BARC [Iy] group have found amounts of tritium comparable to the Bockris group in the D₂O electrolyte from cells in which electrolysis was carried out for a few days with currents varying between 1 to 100 amperes. As was already mentioned above, here there is again a factor of 1000 internal inconsistency between their measured neutron yields and the neutrons that have to be there if this tritium was indeed produced by fusion -- even if one assumes the very unlikely drastic modification of the branching ratio in the D + D reaction.

The experiments carried out to date include the large number of null experiments. There are a few experiments in which excess tritium is found, and which other groups have not been able to reproduce. These measurements also contain a serious internal inconsistency, in that the ratio of measured neutrons to tritium is smaller by orders of magnitude than what is consistent with a fusion process being their source. Additional investigations are desirable to clarify the origin of the excess tritium that is occasionally observed.

VI. EXOTIC EXPLANATIONS

The data on fusion products, even where positive results are reported, give rates far below those that would be expected from the levels of heat reported in some electrolysis experiments. There have been some attempts to propose mechanisms where the reaction heat from the D + D → ⁴He process would go entirely into lattice heat, rather than a photon [Wal, Ha]. Analogies have been made with the internal conversion process, and with the Mossbauer effect. Neither of these analogies is applicable to ⁴He.

Internal conversion allows an atomic electron of an excited nucleus to carry off the reaction instead of a photon. This process is understood quantitatively -- it is dominant in heavy atoms with tightly bound inner electrons and for low energy (less than 1 MeV) photons. In helium the atomic electrons are loosely bound and the photon is 23.8 MeV -- there can not be any appreciable coupling between the photon and the atomic electrons, and internal conversion or any related process cannot take place at anywhere near the rate that would be required.

In the Mossbauer effect the momentum of a very low energy (below 100 keV) photon is taken up by the entire lattice in a coherent mode, but not its energy. The process cannot be relevant to the present process.

Considering experimental evidence more generally, there have been careful studies of a very large number of reactions analogous to the D + D fusion process, in which gamma rays of comparable energy emitted from low-energy nuclear reactions (thermal-neutron capture gamma rays) and the cross sections for capture have been studied very carefully and quantitatively. Their knowledge is essential to the operation of fission reactors. If there were any anomalous processes in which the energy of a capture gamma ray were converted into lattice heat, this would have almost certainly been noticed as a discrepancy in cross sections with major implications for the operation of reactors. After four decades of extensive study of the processes relevant to

the operation of fission reactors the possibility is extremely remote that an entirely new process, that could dominate these nuclear reactions, would have remained hidden.

VII. SEARCH FOR PRODUCTS OF COLD FUSION IN THE EARTH

Products of low-level cold fusion have been inferred to be produced by natural geologic processes [Jo, Jo1]. The $^3\text{He} : ^4\text{He}$ ratio is anomalously high in volatiles from deep-source volcanoes such as Hawaii, Iceland, and Yellowstone [Cr, Ku, Mam]; anomalous ^3H is also suggested by fragmentary data [Om, Jo2], and production of other radiogenic products such as ^{36}Cl have been predicted [Pk]. Although the high ^3He values have previously been considered relict from early earth processes, presence of anomalous ^3H or ^{36}Cl (beyond that due to bomb tests) would be definitive evidence of natural cold fusion at depth within the earth. Implications would be major for geophysical problems such as heat-flow modelling, element-distribution with depth, and composition of the Earth's core.

Although some ~~knowledgeable~~ isotope geochemists see no evidence for naturally occurring cold fusion [Cr1], several government and university labs are searching for evidence of such fusion processes as recorded by volcanic volatiles [Jo2, Ky, Go, Loc, Qu]. Even if laboratory experiments for cold fusion are discredited, such geologic studies could add much to understanding of the behavior of volcanic volatiles. No rigorous results are yet available, but experiments proposed or underway at Brigham Young, Los Alamos, Lawrence Livermore, New Mexico Tech, and the U.S. Geological Survey (Denver) should yield data within 6 months to 1 year.

VIII. SUMMARY

A number of careful experiments have been carried out to search for the expected products of cold fusion. None have seen these products at anywhere near the level that would be expected from the heat production reported in electrolysis, by many orders of magnitude. Some experiments report neutrons or tritium at a much lower level -- however, the rates of these two fusion products (measured in the same experiments) are inconsistent with each other, again by large factors.

The neutron bursts reported in some experiments also suffer from not being reproducible by other experimenters. While it is conceivable that some mechanism might produce very small bursts of hot fusion (e.g. high voltage internal sparks associated with fracture of the material at certain temperatures), at the present time the experimental evidence is not readily reproducible, and if real, the phenomenon does not appear to be related to "cold fusion" as postulated in the heat production experiments.

If there were such a process as room temperature fusion, it would require not only

- (a) the circumvention of fundamental quantum mechanical principles, which have been carefully tested against numerous measurements of barrier penetration (such as the systematics of spontaneous fission and alpha radioactivity lifetimes and those of nuclear cross sections), but also

- (b) drastic modifications of branching ratios in the D + D reaction, and
- (c) the invention of an entirely new nuclear reaction process.

A quotation from Lewis Carroll seems appropriate:

~~'Alice laughed. "There's no use trying," she said: "one can't believe impossible things."~~

~~"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."~~

New Energy Times Archive

TABLE I. SOME COLD FUSION NEUTRON RATES

Authors	Reference	Neutrons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
Yield corresponding to 1 watt of heat production [Fle]		3×10^{-11}	3×10^{12}
Yield corresponding to neutron yield of Jones et al. [Jo]		10^{-23}	1
Broer et al [Br]		$< 2.2 \times 10^{-24}$	< 0.2
Williams et al [Wi]			< 0.2
Lewis et al [Le]		$< 1.5 \times 10^{-24}$	$< .15$
Alber et al [Alb]		$< 5 \times 10^{-25}$	< 0.05
Gai et al [Ga]		$< 2 \times 10^{-25}$	< 0.02
Schriber et al [Schr]			< 0.02
Kashy et al [Ka]		$< 10^{-25}$	< 0.01
De Clais et al [DeCl]			< 0.01
			< 0.001

[a] assuming that neutrons are produced throughout the volume.

TABLE II. SOME COLD FUSION FAST CHARGED PARTICLE RATES

Authors	Reference	Protons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
<hr/>			
Yield corresponding to 1 watt of heat production [Fle]		3×10^{-12}	3×10^{12}
Jones et al.	[Jo]	1×10^{-23}	1.0
Rehm et al.	[Reh]	$< 4 \times 10^{-23}$	< 4
Schrieder et al.	[Schr]	$< 3.1 \times 10^{-24}$	< 0.31 [b]
Sundquist et al.	[Su]	$< 2 \times 10^{-24}$	< 0.2
Ziegler et al.	[Zi]	$< 1.2 \times 10^{-24}$	< 0.12 [b]
Porter et al.	[Po]	$< 6.7 \times 10^{-25}$	< 0.07
Price et al.	[Pr]	$< 8.3 \times 10^{-26}$	< 0.008
<hr/>			

[a] assuming that particles are produced throughout the volume of Pb

[b] 6. Rehm et al comment that the choice of the low-energy cutoff (e.g. 1 MeV in Ref. [Zi]) restricts the emission angle of the protons with respect to the foil to a small cone representing only a few of the total solid angle. This effect seems to have been neglected in the efficiency calculations for the limits quoted by these authors.

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APPENDIX A

NEUTRON DETECTION.

Neutrons from dd fusion can be detected either at their initial energy in the MeV range as "fast" neutrons, or their energy has been "moderated" by sharing it in successive collisions with light material -- particularly hydrogen. Fast neutrons can be detected by photomultiplier tubes viewing the proton recoil in plastic or liquid scintillation material. Slow neutrons (those that have lost almost all their kinetic energy and are in thermal equilibrium at room temperature) are conventionally detected by the charged particles produced when the neutron is captured with high probability in the nucleus of an atom of ^{10}B (producing an alpha particle), or in a ^3He nucleus, producing a recoil proton. A noble gas, ^3He is used in the form of a proportional counter, while boron can be used either in the form of BF_3 proportional counters or in the solid form, with the boron immersed in plastic or inorganic scintillator viewed by a photomultiplier.

Additionally, neutrons can be detected after moderation by their capture in some material of very high capture cross section (such as cadmium Cd), which produces several gamma rays that may, in turn, be detected by a photomultiplier viewing a scintillation detector. Similarly, neutrons moderated in water are almost entirely captured on the protons ("radiative capture"), giving rise to a deuteron plus a gamma ray with 2.2 MeV.

Finally, moderated neutrons may be captured in a trace element in the moderator (silver is a detector of choice) to produce a radioactive material that can be transported away from the experimental apparatus and counted separately with high efficiency at low background. The emitted radiation is typically a beta ray (negative electron), or a characteristic gamma ray following the beta decay. Of course, the world has enormous experience since the 1930s in detecting neutrons and in detecting neutrons from the D + D fusion reaction.

APPENDIX B

CONSIDERATIONS IN TRITIUM CONCENTRATIONS.

Tritium is produced in the atmosphere by cosmic ray bombardment. Most of such tritium ends up in the oceans and in rivers. The "natural" abundance of tritium varies widely and was greatly increased by atmospheric testing of thermonuclear weapons in the '50s and in the early '60s. The order of magnitude of tritium in ordinary water is $\text{T/H} - 10^{-18}$ (1 TU). Sources vary from 1 to 200 TU. The production of heavy water from ordinary water is even more efficient in the enrichment of tritium than deuterium from the feed material. Most of the heavy water currently available is produced by the $\text{H}_2\text{S} - \text{H}_2\text{O}$ dual temperature exchange process (GS process). The tritium content of fresh heavy water produced by the GS process is 68 dpm/ml $\text{D}_2\text{O}/\text{TU}$ feed. Processes that are more efficient than the GS process in heavy isotope enrichment will have a minimum tritium specific activity of 50 dpm/ml $\text{D}_2\text{O}/\text{TU}$ feed. Heavy water currently being sold on the open market has a specific activity in the range 120 - 180 dpm/ml D_2O . There are sources of D_2O with specific activity as high as 10^4 dpm/ml.

Most of the work done to date on the search for tritium produced in the electrolysis of D₂O in cells with palladium cathodes has been done in open cells. The measurements are frequently limited to assays of the specific activities of the starting D₂O and the electrolyte after electrolysis. In general, there have been periodic additions of D₂O to replace the D₂O decomposed to form palladium hydride and D₂(gas). To determine how much tritium, if any, has been produced requires a complete inventory of the tritium at the beginning and end of the experiment. From the data on the current and on the duration of the electrolysis it is possible to estimate the amount of D₂O which has been electrolyzed. Electrolysis will enrich the tritium in the D₂O of an electrolytic cell. The amount of enrichment is primarily a function of the amount of water electrolyzed for a given type of cathode. It can reach a factor of 5 when 95% of the initial charge of water is electrolyzed. Thus a careful analysis of an electrolytic experiment must be carried out if one is to interpret specific activities of tritium after electrolysis, below 1000 dpm/ml of D₂O, as anything other than electrolytic enrichment [Bi].

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Dear Dr. Snykers:

Thank you very much for your note of 09/25/89 and the attached FT/MOL/89-06 "Experimental Evidence of Erroneous Heat Production in Cold Fusion Experiments," by A. Bruggeman, et al.

As you may know, I am a member of the Cold Fusion Panel of the Energy Research Advisory Board, and am on my way today for a one-day meeting in Chicago, to prepare a draft of our final recommendations for the Secretary of Energy. I shall certainly bring this report to the attention of my colleagues.

Incidentally, I have been aware of the possibility that measurements of steady current and voltage might seriously underestimate the electrical power dissipated in the cell. I included the attached foil in my briefing to the National Science Board in Washington 05/12/89, and also to the Cold Fusion Workshop in Santa Fe, 05/24/89. Of course, the foil is an exaggerated case, but it was just to illustrate how big an error one might make if the system of regulation oscillated.

I visited only one laboratory among the various site visits made by our Panel. Unfortunately, we were never shown a cell claimed to be producing excess heat, so my threat to apply an oscilloscope probe to the voltage leads was always an empty one.

Thank you for your thoughtfulness in sending the report.

Sincerely yours,

Richard L. Garwin

Encl:

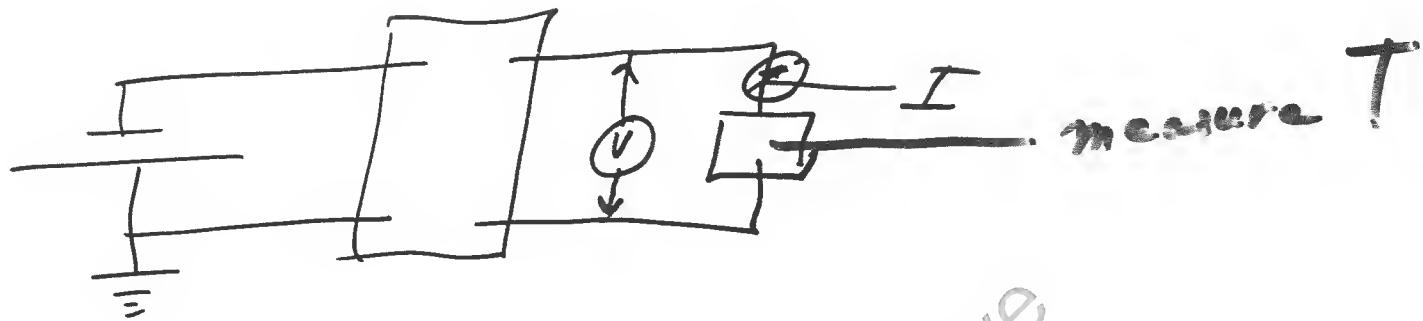
-05/12/89 Copy of foil used in RLG briefing to the National Science Board and to the Cold Fusion Workshop.

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(12)

05/12/89

Not even so easy to calculate [1]
 "power in":



I have put in $I = 0.1 \text{ A}$

$$V = 200 \text{ V}$$

and dissipated $200 \text{ W} \gg V \times I$

$$\bar{P} = \langle V(t) \cdot I(t) \rangle$$

$$\text{If } V \text{ is constant } \bar{P} = V \langle I(t) \rangle$$

$$\text{if } I \text{ is constant } \bar{P} = \langle V(t) \rangle I$$

But if not, $\bar{P} \neq \langle V(t) \rangle \times \langle I(t) \rangle$



Date: 10-OCT-1989 12:24:37.58
From: "SCHIFFER@ANLPHY (312)972-4066 FAX:972-3903" <SCHIFFER@ANLPHY>
To: rlg2@yktvmv.BITNET
Subject:
X-ANJE-To: KOONIN,GARWIN,SCHIFFER

Enclosed is the draft that will be at the Thursday meeting. I decided to cut down on the Oppenheimer Phillips discussion, just say that the approximation is not valid for D+D -- without detailed explanation. I was not happy with either version -- making a quantum mechanical explanation in a document that is for public consumption is difficult. It can be done if essential, but I see it as a minor point, and the elaboration gives it more emphasis than it deserves, in my view. We can discuss it further if necessary.

John

New Energy Times Archive

Draft -- October 10, 1989

FUSION PRODUCTS

I. INTRODUCTION

The nuclear fusion of deuterium has been studied intensively for over 40 years. The reaction between two low energy deuterium nuclei can proceed in three ways:

- (a) $D + D \rightarrow ^3He + n + 3.269 \text{ MeV}$
- (b) $D + D \rightarrow ^3H + p + 4.037 \text{ MeV}$
- (c) $D + D \rightarrow ^4He + \text{gamma}(23.847 \text{ MeV})$

The reactions (a) and (b) have been studied down to deuteron energies of a few keV and the cross sections found to be equal to within 10%. In the interaction of deuteron beams with heavy ice or metal deuteride targets, almost one 2.45 MeV neutron is produced (with an accompanying 3He) for every triton (with an accompanying proton). This near-equality of neutron and proton branches of the $D + D$ reaction, shown in figure 1, is a reflection of the basic symmetry of nuclear forces between proton and neutron, disturbed only slightly at the MeV energies of the emerging particles by the Coulomb interaction, which is not symmetrical between proton and neutron. The cross sections for reaction (c) are very small -- on the order of $10^{**}7$ lower than the first two.

All nuclear reactions at low energies between two deuterons are retarded by the Coulomb repulsion between the positively charged nuclei -- the penetration of the repulsive Coulomb barrier changes exponentially with bombarding energy: for instance the measured cross section for reaction (b) changes from 0.2 microbarns at 2.7 keV to 35 millibarns at 100 keV. But the r_a_t_i_o_s for the three reactions appear to be constant below 100 keV.

Any fusion between deuterium nuclei m_u_s_t lead to detectable fusion products. For reaction (a) neutrons are the most easily detected product, by direct counting. For (b) the protons or tritons can be detected by direct counting, and the accumulated tritium could also be identified by its radioactivity, albeit with lower sensitivity. However, neutron counting is perhaps again the most useful technique here, since neutrons must be produced by the energetic tritons interacting with other deuterons in the material at the rate of 1 neutron for every 10,000 to 50,000 tritons. Reaction (c) leads to readily detectable high energy gamma rays and 4He ; the latter may be identified by mass spectroscopic measurements whose the sensitivity is low -- though the $10^{**}17$ levels implied by 1 watt of heat should be readily observable.

In the following we summarize the experimental evidence on these fusion products. First we discuss the plausibility of reactions at room temperature and the issue of whether the constancy of the three reaction modes is a reasonable extrapolation to very low energies. Then the data on neutrons, charged particles, gamma rays and tritium are summarized. Finally, some comments are included on the more exotic explanations, and geophysical evidence is summarized on proposed cold fusion in the interior of the earth.

II. THE REACTION PROCESS.

Fusion reactions can occur only if during a nuclear collision the Coulomb barrier is surmounted or, at low energies, penetrated so that the nuclei approach each other within about 10^{**-12} cm. This distance is some 10,000 times smaller than the typical separations of atoms in ordinary matter. The penetration of the barrier at low energies takes place through a well understood quantum mechanical phenomenon called tunneling that allows fusion to occur in collisions far less violent than might be required otherwise.

In the thermonuclear fusion that occurs in stars and in laboratory "hot fusion" experiments, very high temperatures provide the violent collisions required to produce fusion. However, in the so-called cold fusion experiments, it is claimed that the penetration of the barrier through quantum mechanical tunneling has somehow become so effective as to allow fusion to occur even at room temperatures. Further, some of the experimenters claim that the nuclear process is changed by some unspecified mechanism so as to alter dramatically the nature of the reaction products. Each of these claims must be understood as separate and equally surprising.

Some simple calculations serve to illustrate how remarkable the claim of fusion at room temperatures really is. The fusion rate for the two deuterium nuclei in a deuterium molecule (where they are even closer than they are when embedded in a metal) results in one fusion per year in a solar mass of deuterium. Further, the fusion of protons and deuterons is 10^{**9} times faster than the D + D reaction claimed to have been observed (although it is still extraordinarily slow). There is no known mechanism by which these rates c_o_u_l_d be enhanced by the 40-50 orders of magnitude required to agree with the reported observations.

One commonly invoked mechanism for enhancing cold fusion rates is screening by "heavy" electrons. It is true that endowing the electron with a hypothetical mass some 5-10 times larger than it actually has would enhance fusion rates sufficiently to agree with most cold fusion claims [Ko]. It is also true that there are "heavy fermion" materials whose thermodynamic properties at very low temperatures are characteristic of quasiparticles with masses many times those of a free electron. However, this phenomenon is understood as involving long-wavelength excitations in which strong correlations "dress" electrons near the fermi surface. As such, heavy fermions extend over many lattice sites. Because the tunnelling in nuclear fusion occurs at distances smaller than one lattice site, only the short-wavelength "bare" electron excitations are relevant for screening, and cannot enhance the fusion rate significantly.

IIa. The D + D Branching Ratios.

The relative rates of reactions (a), (b), and (c) are called the branching ratios and are a crucial issue in the discussion of some cold fusion claims. These reactions have been studied in laboratory experiments using accelerators for deuteron energies above a few keV [Kr]; the smallness of both cross sections prevents reliable measurements at lower energies. The ratio between the two rates exhibits a weak energy dependence and is near 1.0 at the lowest energies as seen in figure 1. Data from muon-catalyzed D + D fusion [Bal], which probes an even lower energy range is still consistent with nearly equal rates.

A branching ratio of more than one million would be required to explain experiments that claim to observe high fusion rates (either through

heat or tritium production) without a corresponding high neutron flux. As "cold fusion" is thought to occur at energies on the order of eV, this is not directly ruled out by the data discussed above. However, there is no known mechanism for inducing such a rapid energy-dependence in the branching ratio. The Oppenheimer-Phillips process involving the Coulomb break-up of the deuteron has been invoked in this regard. However, this approximation is not valid at the low energies of the D+D system.

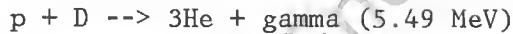
IIb. The Gamma Branch.

Some researchers have hypothesized that the $D + D \rightarrow 4\text{He} + \gamma$ (23.847 MeV) reaction, which is ordinarily some 10^{**7} times weaker [Bar] than reactions (a) and (b) in which two fragments are produced, somehow dominates in cold fusion situations. To be consistent with the lack of neutrons, a very large enhancement of the gamma branch by a factor somewhere in excess of 10^{**13} would be required. We know of no way whereby the atomic or chemical environment can effect such an enhancement, as this ratio is set by phenomena on a length scale some 10^{**4} times smaller than the atomic scale.

Even if there were such an enhancement, the absence of observed high-energy electromagnetic radiation (photons, positrons, or fast electrons) rules out such a mechanism. While direct coupling to the lattice through unspecified mechanisms has been invoked to suppress such radiation, any such coupling must occur through the electromagnetic field and would result in s_o_m_e observable high-energy radiation.

IIc. The p + D Reaction.

It has been suggested an alternative fusion process could be the reaction



for which the penetration factors are still overwhelmingly small at room temperature, but somewhat less so than for the D + D process [Ko]. This reaction must produce a readily observable gamma ray and, if it is to account for 1 watt of heat, then it should also produce 3He in observable concentrations.

IId. Estimate of Secondary Yields from Fusion Products.

i) Neutrons from tritium. The tritons produced in reaction (b) are produced with an energy of 1.01 MeV. This energy must be lost in the immediately surrounding material, which in the case of an electrolytic cell is either the Pd electrode saturated with deuterium, or heavy water. The tritons will therefore bombard the deuterium in the surrounding material. The t+d reaction is a rich source of neutrons, with a cross section that reaches 5 barns at 0.12 MeV, then falls to about 0.7 barns at 0.5 MeV, and reaches slightly below 0.3 barns at 1 MeV. For the 1.01 MeV tritons from the D + D reaction one may assume an average cross section of about 1.2 barns. For tritons that are stopped in PdD this translates into a neutron yield between 0.15 and $0.2 \times 10^{**-4}$ neutrons per triton; for tritons stopping in heavy water there are about $0.9 \times 10^{**-4}$ per triton.

ii) Coulomb excitation of Pd by protons. The even Pd isotopes (104, 106, 108, 110) with abundances of 11, 27, 26, 12 % have first-excited 2+

states at 555,512,434,374 keV and B(E2) values between 0.5 and 0.8 barns. The cross sections for Coulomb excitation are in the vicinity of 20 to 50 mb and thus the yields expected are 2 to 5 10^{**-6} per proton. In palladium the half thickness for absorption of these gamma rays is about 4 mm, in water it is several cm.

In terms of power, there must be about 10^{**8} /sec secondary neutrons per watt of fusion, even if direct neutron production is completely suppressed and all the reaction goes into tritium production. Under these conditions there must also be slightly under 10^{**7} secondary photons per second, of well defined energies, in the 500 keV range.

III. NEUTRONS.

IIIA. Detection.

As discussed above neutrons are a major product of D + D fusion. Neutrons are very convenient particles to detect, since they interact only with the nuclei of atoms and so can emerge from reaction vessels of substantial size unscathed and without having lost any energy. Similarly, large counters can be used without the problem of thin entrance windows, since neutrons enter into the volume of the counter without difficulty. Some simple facts about neutron detection are summarized in Appendix A.

IIIB. Selection of Data.

In what follows, we have tried to use published material, where available, or material prepared for publication and presented at formal meetings or as preprints distributed without restriction as to citation. It is important to include not only p_o_s_i_t_i_v_e results, that claim the detection of neutrons, but also the n_e_g_a_t_i_v_e ones, that have attempted to replicate the experimental procedure of the former and failed to detect neutrons at a level of sensitivity substantially better than the positive results.

IIIC. Initial claims.

The University of Utah (UU) group in its i_n_i_t_i_a_l publication [Fle] claimed the detection of neutrons from D + D by virtue of the gamma ray emitted by the capture of the moderated neutron in the water bath surrounding the electrolytic cells. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper, considerably narrower than is consistent with this type of detector, and with internal inconsistencies in the energy scale.

These very questions were taken up by a group at MIT, [Pe] who showed that the photo peak at 2.2 MeV obtained at MIT from Cf spontaneous fission neutrons moderated in water and radiatively captured on protons is accompanied by other peaks from natural background that enable one to calibrate the energy, and successive interchange between UU and MIT groups in the scientific literature has demonstrated that the claimed detection of neutrons by the proton capture gamma ray at UU has been an artifact of the experimental apparatus.

The original publication from Brigham Young University (BYU) [Jo] presented the detection of neutrons as the sole experimental evidence for the existence of cold nuclear fusion. The neutrons were detected in a two-stage neutron counter -- first by the proton recoil in organic

scintillator, followed within a few tens of microseconds by a signal from the capture of the moderated neutron on boron viewed by the same photomultipliers. This double detection of a single neutron serves substantially to reduce the ambient background due to gamma rays, although there remains background in the experiment due to gamma rays and to real neutrons from cosmic rays* and other sources. The group at BYU has chosen to attempt to vary the experimental conditions in order to obtain a greater rate of D + D fusion, and so has not presented much more data than the original paper on the detection of neutrons with that counter. In fact, BYU has been working in collaboration with other groups, notably at LANL [Me], and also with a group at Yale University. The original claim of neutron detection five standard deviations above the background is somewhat reduced in statistical strength if one considers the degrees of freedom that are fixed by the presentation of a peak in one of a number of experiments and at a particular energy, and also the possible fluctuation in the cosmic-ray neutron background. Ordinarily, however, such a result can be improved by using different counting or detection equipment or by reducing background through improved shielding or by moving to underground site.

*(footnote) Additional care is needed as the rate of cosmic ray neutrons can fluctuate by 20% or more with variations in barometric pressure or with solar activity.

Typical of the latter is work presented by the group at Sandia National Laboratory, [Ald] in which a site was found with substantially less background and results presented as follows for a limit on the neutrons produced in electrolytic fusion. Similar results from the Frejus tunnel in [France were also presented at SantaFe [DeCl].

Many claims have been made for the production and detection of neutrons produced in electrochemical cells, but these claims have almost all been withdrawn or moderated by the discovery of difficulties with the counter -- particularly with the BF₃ counters used. In some cases, the counters are sensitive to humidity; in others to microphonic noise (vibration); or to other afflictions. A summary of some of the limits on neutron fluxes reported, compared to the flux reported by the BYU group, is shown in Table I.

III d. Dry Fusion.

Results presented in April 1989 by a group at Frascati [DeN] opened an entirely new opportunity for the observation of D + D cold nuclear fusion. In this work, deuterium gas at 60 atmospheres pressure (60 bar) was allowed to contact titanium lathe turnings in a stainless steel reaction vessel. That allowed the temperature of the sample to be varied either by heating or by cooling. No neutrons were observed from the hydriding reaction at room temperature or at elevated temperature, when viewed by a nearby BF₃ counter. However, after cycling to nitrogen temperature, b_u_r_s_t_s of counts were obtained from the counter -- typically on the order of 20 counts per burst emerging over a period of 60 microseconds. One set of data was presented on counts obtained by cycling to nitrogen temperature, showing neutrons essentially only in these bursts.

A totally different type of neutron emission was also claimed by the Frascati group [DeN] following warming from nitrogen temperature over one weekend. A bell-shaped curve rising to a peak of 300 neutrons per ten-

minute counting interval extended over some five hours. This, of course, is an important experimental result, and provoked great effort toward verification both at Frascati and elsewhere. A recent private communication from M. Martone at Frascati indicates that there has been no confirmation of either the burst results or of the continuous neutron emission from the D-Ti system or from any other dry fusion activity at Frascati. In addition, electrochemical cells operated without producing observable numbers of neutrons, and their operation was terminated during the month of July.

A group at LANL [Me] has conducted dry fusion work with Ti and Pd, and has presented results both at the Santa Fe meeting and in a preprint. This group at LANL uses high-efficiency systems that moderate any fast neutrons emitted from experimental cells, detecting the moderated thermal neutrons in ^3He gas counters. Bursts of neutron counts are sometimes observed 3000-5000 seconds after the sample is removed from liquid nitrogen, at a time when the sample temperature is typically -30 C. These bursts, consisting of about 100 neutrons at most, are seen in about 30% of the samples tested. An attempt to reproduce this effect at Sandia National Laboratory yielded entirely negative results. [Ald]

At the Santa Fe workshop, Moshe Gai of Yale presented results obtained in collaboration with Brookhaven National Laboratory, in which no neutrons were detected from electrolytic cells. [Ga]

Finally, a conference report from the Bhabha Atomic Research Center (BARC), [Iy] provides text and tabulated results from several groups at BARC. Fig. 1 of the BARC report shows counts from neutron detectors observing a large electrolytic cells, with an estimated 2×10^{17} neutrons in the 5 minutes following an overpower trip of the electrolyzer. Tritium and neutrons are reported to be observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd. Fig. 2 of the BARC report shows dry fusion ^3He counter output during gradual rise of temperature of 20 g of Ti while deuterium gas was being pumped off. It is also commented that samples could be loaded with deuterium gas at 1 bar and 900 C, and that "one such disc shaped button loaded on Friday 16th June began emitting neutrons on its own, almost 50 hours after loading. It produced (about) 10^{16} neutrons over a 85-minute active phase. The background neutron counter did not show any increase in counts over this time."

IIIe. Secondary Neutron Production.

There are severe problems of consistency between the number of tritium atoms found in some of the experiments discussed above and the number of neutrons detected. The BARC abstract reads, "The total quantity of tritium generated corresponds to about 10^{16} atoms suggesting a neutron to tritium branching ratio less than 10^{-8} in cold fusion."

But, as discussed above there m_u_s_t be at least one neutron per 100,000 tritons if the observed tritium were originating from fusion, _1_0_0_0 times more than was observed!

IV. CHARGED PARTICLES AND GAMMAS.

A few experiments [Po,Pr,Re,Su] to measure the 3 MeV protons and/or the 1 MeV tritons produced in the reaction, $\text{D} + \text{D} \rightarrow 3\text{H} + \text{p}$, have been

reported; they are summarized in Table II below. A variety of different methods has been used, but the lowest limit on charged-particle production appears to be that set by Price using plastic track detectors. Their setup was designed so that the light water control cell matched the heavy water cell as closely as possible. Electrolysis was performed for 13 days, and the cathode stoichiometry was determined to be Pd(H,D)0.8. Both cells showed track production rates that agreed and were consistent with the alpha-particle emission rate for native Pd foils due to trace (ppm) impurities of the natural 238U and 232Th decay chains; however, no tracks due to protons with energies between 0.2 and 3 MeV or tritons with energies between 0.2 and 1 MeV were found. From these data Price [Pr] set limits on the fusion rate of less than 0.002 per cm³ per second. This value results in an upper limit of 8.3×10^{-26} fusions per dd pair per second. This is about an order of magnitude lower than the limits obtained using Si surface barrier (SSB) techniques.

A limit on the fusion rate of 0.028 per cm³ per second or 1.2×10^{-24} fusions per dd pair per second was obtained by Ziegler [Zi] using a SSB technique. Porter [Po] used a SSB detector to view the back of a 76 micron thick Pd foil cathode in a heavy water electrolysis cell. They obtained a limit of less than 6×10^{-25} protons per dd pair per sec at the 2 sigma level; chemical analysis of their electrolytes showed no evidence for anomalous increases in tritium concentrations. Sundqvist et al. [Su] also used a SSB technique to detect protons. The detector was placed close to Pd foil cathodes that were thin enough to allow all the protons produced to escape from the foil. All of their runs gave a null result within the statistical errors, resulting in a fusion rate of $-2.1 (+/- 2.2) \times 10^{-24}$, if a bulk process is assumed.

Recently, Rehm [Re] has reported using a proportional counter to search for charged particles from electrolytic cells with Pd and Pt electrodes in 0.1 M LiOD in D₂O. They obtained an upper limit of 4×10^{-23} fusions per dd pair per second, not as low as the limits using the other methods.

In summary, a variety of experimental techniques has been used in searches for charged particles; all of them set very low limits on fusion occurring via the D + D \rightarrow 3H + p. Most of these results set limits that are considerably less than Jones' [Jo] value of $1.00 (+/- 0.82) \times 10^{-23}$ fusions per dd pair per second for the D + D \rightarrow 3He + n channel obtained from neutron measurements. (The uncertainty was calculated by [Su]).

The upper limit of Price [Pr] of 8×10^{-26} fusions per dd pair per second is much below the average low rate inferred from the neutron measurements of Jones or even those of Menlove [Me]. The extremely low limits which the searches for charged particles (either protons or tritons) place on their production is clearly inconsistent with the reported production of tritium via the cold fusion reaction.

IVa. GAMMA-RAY SEARCHES

As was mentioned above, a rare branch of the D + D reaction proceeds through capture, in which a 23 MeV gamma-ray is emitted. Similarly, the p + D reaction is associated with a 5.49 MeV gamma ray. Several searches have been published in which no gamma rays that would be associated with the D + D or p + D capture reactions were seen. They include a report by Henderson [He] who cites limits around $10^{-23}/\text{sec}$ 23 MeV gamma rays emitted per deuteron in various cells. Porter [Po] reports no 5.5 MeV gamma rays -- though no absolute limit is quoted. They also comment on the absence of Pd K X-ray production. Greenwood [Gr] also

report limits of 10^{**-23} for gamma rays above 1.9 MeV. Other negative results are quoted in the Santa Fe abstracts without quantitative detail.

V. TRITIUM.

As discussed above, one branch of the D + D reaction produces tritons and protons. As was also discussed, searches involving the direct detection of charged particles have yielded rather stringent negative results; so have the lack of neutrons. A number of searches have also been made for the tritium accumulated during the electrolysis of D₂O with palladium cathodes, determining tritium content by detecting the radioactive decay of tritium. In such experiments it is important to determine the initial tritium content of the heavy water and recognize the fact that the electrolysis of the heavy water will enrich the naturally occurring tritium in the heavy water.

The detection of tritium by measurement of its beta decay is inherently a less sensitive probe of the D + D reaction than the direct measurement of neutron production or charged particle production. About 10^{**7} tritium atoms give 1 decay by beta emission per minute. The tritium content of normal water is about 10^{**-18} relative to hydrogen but, as discussed in Appendix B the normal manufacturing of heavy water also enriches in tritium and thus heavy water currently being sold gives between 120 and 180 disintegrations per minute (dpm) from tritium decay.

Va. Null Experiments.

Most of the work reported to date on the search for excess tritium produced in electrolytic cells can be accounted for by the electrolytic enrichment process. This includes the original report by Fleischmann and Pons [Fle], and experiments at ANL, Gre, Red BNL, Da, McB, Wi2, Cal Tech, Le2, CRNL, Sc, INEL, Lo, LLNL, Al, NRL, Er, ORNL, Fu, Sc, Sandia, Na, SRL, Ra, Texas A & M, Ma, and Utah, Wad.

Vb. Tritium Bursts.

A small number of experimenters report occasional irreproducible amounts of excess tritium in their D₂O samples taken from their electrolytic cells after days of operation. This includes observations by Storms, St, at Los Alamos, and Fuller [Fu] and Scott [Sc] at ORNL. The ORNL experiments show single cases of an excess of tritium which is of short duration, after which a cell returns to background level. Storms reports excess tritium, 100 times background, in two cells out of fifty.

Vc. Closed Cells - Correlation with Excess Heat.

Four different groups [McB, McC, Sc, Ma] have now looked for tritium production in closed electrolytic cells. These experiments detect all the tritium from the electrolytic process with the exception of that which may be contained in the Pd cathode. In general, the deuterium inventory in the cathode is negligible compared with the D₂O. Only that tritium formed within the cathode and which remains there because of slow diffusion is unaccounted for. There is no electrolytic enrichment of the tritium in the make up D₂O. In these experiments the total amount of excess tritium formed in the total D₂O is less than 10^{**4} T atoms/sec. If this tritium is produced by the D + D reaction, then the maximum amount of excess power (cold fusion power) is 10^{**-5} milliwatts. In one experiment [Wad] in an open cell there was a heat burst of 35 watts for 90 minutes (187,000 joules). The tritium was measured after the burst and no excess above the

electrolytic enrichment was found. Clearly the heat burst does not come from the D + D reaction.

Vd. High Levels of Tritium.

Two groups [Pa, Iy] find tritium at levels of 10^{**12} to 10^{**14} T atoms/ml D₂O after periods of electrolysis of the order of hours. This amount of tritium cannot be produced by electrochemical enrichment with the D₂O volume reductions reported. The results of the Bockris [Pa] group at Texas A & M for cells in which excess tritium was found are given in Table 1 of their paper. Excess tritium is not found in all of their cells. A listing of cells in which no excess tritium was found is given in their Table 4. The Bockris cells are 0.1 M in LiOD and have nickel anodes. They precipitate nickel oxide during the electrolysis; some nickel is also electroplated out on the palladium cathode. In one experiment, A8, the specific activity of the D₂ gas produced by the electrolysis was measured. It is 100 times that of the electrolyte.

D₂(gas) containing tracer amounts of tritium and in equilibrium with D₂O(liquid) has a specific activity that is lower by 0.6 than the D₂O (liquid). If the tritium is formed during electrolysis, this result suggests that it is formed in the chemical species DT and that the tritium in the liquid D₂O is the result of hot atom processes or slow isotopic exchange of the DT(gas) with D₂O(liquid) Bi₂.

Wolf Wo^l at Texas A & M have looked for neutron production in Bockris type cells. An upper limit to their neutron production rate is 1 neutron/second, which is 10^{**-10} times that of the tritium production rates reported with similar cells by Packham et al. [Pa]. This is a large discrepancy from the equal production rates for neutrons and tritons required by the branching ratio in the fusion reaction, discussed in section II, and is inconsistent, by a factor of 10,000 to 100,000, even with the secondary neutrons that m_u_s_t accompany the tritons produced from nuclear fusion. One is strongly inclined to conclude that the excess tritium found in the electrochemical cells cannot be the result of nuclear fusion in the cell.

The most extensive and systematic search for tritium in the electrolysis of D₂O with Pd cathodes has been carried out by Martin [Ma] at Texas A & M. He has used both open and closed cells. His cathodes come from either Johnson & Mathey, a major supplier, or Hoover and Strong, who supplied the cathodes to the Bockris [Pa] group. He has operated cells with Pt, Ni wire and Ni gauze (obtained from Bockris) anodes. In none of his cells does he find any excess tritium beyond that expected from electrolytic enrichment. Nor does he find any neutrons. Two of his cells produced excess heat but no tritium. In short, he has been unable to reproduce the results of the Bockris group.

The BARC [Iy] group have found amounts of tritium comparable to the Bockris group in the D₂O electrolyte from cells in which electrolysis was carried out for a few days with currents varying between 1 to 100 amperes. As was already mentioned above, here there is again a factor of 1000 internal inconsistency between their measured neutron yields and the neutrons that have to be there if this tritium was indeed produced by fusion -- even if one assumes the very unlikely drastic modification of the branching ratio in the D + D reaction.

The experiments carried out to date include the large number of null experiments. There are a few experiments in which excess tritium is found, and which other groups have not been able to reproduce. These

measurements also contain a serious internal inconsistency, in that the ratio of measured neutrons to tritium is smaller by orders of magnitude than what is consistent with a fusion process being their source. Additional investigations are desirable to clarify the origin of the excess tritium that is occasionally observed.

VI. EXOTIC EXPLANATIONS.

The data on fusion products, even where positive results are reported, give rates far below those that would be expected from the levels of heat reported in some electrolysis experiments. There have been some attempts to propose mechanisms where the reaction heat from the $D + D \rightarrow ^4He$ process would go entirely into lattice heat, rather than a photon [Wal,Ha]. Analogies have been made with the internal conversion process, and with the Mossbauer effect. Neither of these analogies is applicable to 4He .

Internal conversion allows an atomic electron of an excited nucleus to carry off the reaction instead of a photon. This process is understood quantitatively -- it is dominant in heavy atoms with tightly bound inner electrons and for low energy (less than 1 MeV) photons. In helium the atomic electrons are loosely bound and the photon is 23.8 MeV -- there can not be any appreciable coupling between the photon and the atomic electrons, and internal conversion or any related process cannot take place at anywhere near the rate that would be required.

In the Mossbauer effect the m_o_m_e_n_t_u_m of a very low energy (below 100 keV) photon is taken up by the entire lattice in a coherent mode, but n_o_t its energy. The process cannot be relevant to the present process.

Considering experimental evidence more generally, there have been careful studies of a very large number of reactions analogous to the $D + D$ fusion process, in which gamma rays of comparable energy emitted from low-energy nuclear reactions (thermal-neutron capture gamma rays) and the cross sections for capture have been studied very carefully and quantitatively. Their knowledge is essential to the operation of fission reactors. If there were any anomalous processes in which the energy of a capture gamma ray were converted into lattice heat, this would have almost certainly been noticed as a discrepancy in cross sections with major implications for the operation of reactors. After four decades of extensive study of the processes relevant to the operation of fission reactors the possibility is extremely remote that an entirely new process, that could dominate these nuclear reactions, would have remained hidden.

VII. SEARCH FOR PRODUCTS OF COLD FUSION IN THE EARTH

Products of low-level cold fusion have been inferred to be produced by natural geologic processes [Jo, Jo1]. The $^3He: ^4He$ ratio is anomalously high in volatiles from deep-source volcanoes such as Hawaii, Iceland, and Yellowstone [Cr,Ku,Mam]; anomalous 3H is also suggested by fragmentary data [Om,Jo2], and production of other radiogenic products such as ^{36}Cl have been predicted [Pk]. Although the high 3He values have previously been considered relict from early earth processes, presence of anomalous 3H or ^{36}Cl (beyond that due to bomb tests) would be definitive evidence of natural cold fusion at depth within the earth. Implications would be major for geophysical problems such as heat-flow modelling, element-distribution with depth, and composition of the Earth's core.

Although some knowledgeable isotope geochemists see no evidence for naturally occurring cold fusion [Cr1], several government and university labs are searching for evidence of such fusion processes as recorded by volcanic volatiles [Jo2,Ky,Go,Loc,Qu]. Even if laboratory experiments for cold fusion are discredited, such geologic studies could add much to understanding of the behavior of volcanic volatiles. No rigorous results are yet available, but experiments proposed or underway at Brigham Young, Los Alamos, Lawrence Livermore, New Mexico Tech, and the U.S. Geological Survey (Denver) should yield data within 6 months to 1 year.

VIII. SUMMARY.

A number of careful experiments have been carried out to search for the expected products of cold fusion. N_o_n_e have seen these products at anywhere near the level that would be expected from the heat production reported in electrolysis, by many orders of magnitude. Some experiments report neutrons or tritium at a much lower level -- however, the rates of these two fusion products (measured in the same experiments) are inconsistent with each other, again by large factors.

The neutron bursts reported in some experiments also suffer from not being reproducible by other experimenters. While it is conceivable that some mechanism might produce very small bursts of hot fusion (e.g. high voltage internal sparks associated with fracture of the material at certain temperatures), at the present time the experimental evidence is not readily reproducible, and if real, the phenomenon does not appear to be related to 'cold fusion' as postulated in the heat production experiments.

If there w_e_r_e such a process as room temperature fusion, it would require not only

- (a) the circumvention of fundamental quantum mechanical principles, which have been carefully tested against numerous measurements of barrier penetration (such as the systematics of spontaneous fission and alpha radioactivity lifetimes and those of nuclear cross sections), but also
- (b) drastic modifications of branching ratios in the D + D reaction,
a n d
- (c) the invention of an entirely new nuclear reaction process.

A quotation from Lewis Carroll seems appropriate:

'Alice laughed. "There's no use trying," she said: "one can't believe impossible things."

"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

from 'Through the Looking Glass'

TABLE I. SOME COLD FUSION NEUTRON RATES

Authors	Reference	Neutrons per DD pair per sec	Normalized Neutron Yield
Yield corresponding to 1 watt of heat production	[Fle]	$3 \times 10^{**-11}$	$3 \times 10^{**12}$
Jones et al	[Jo]	10^{**-23}	1
Gai et al	[Ga]	< $2 \times 10^{**-25}$	< 0.02
Kashy et al	[Ka]	< 10^{**-25}	< 0.01
Lewis et al	[Le]	< $1.5 \times 10^{**-24}$	< .15
Williams et al	[Wi]		< 0.2
Alber et al	[Alb]	< $5 \times 10^{**-25}$	< 0.05
Broer et al	[Br]	< $2.2 \times 10^{**-24}$	< 0.2
Schriber et al	[Schr]		< 0.02
De Clais et al	[DeCl]		< 0.01 < 0.001

TABLE II. SOME COLD FUSION FAST CHARGED PARTICLE RATES

Authors	Reference	Protons per DD pair per sec	Yield Normalized to Jones et al. neutrons
Yield corresponding to 1 watt of heat production	[Fle]	$3 \times 10^{**-12}$	$3 \times 10^{**12}$
Jones et al.	[Jo]	$1 \times 10^{**-23}$	1.0
Porter et al.	[Po]	< $6.7 \times 10^{**-25}$	< 0.07
Price et al.	[Pr]	< $8.3 \times 10^{**-26}$	< 0.008
Ziegler et al.	[Zi]	< $1.2 \times 10^{**-24}$	< 0.12 [a]
Rehm et al.	[Reh]	< $4 \times 10^{**-23}$	< 4
Sundquist et al.	[Su]	< $2 \times 10^{**-24}$	< 0.2
Schrieder et al.	[Schr]	< $3.1 \times 10^{**-24}$	< 0.31 [a]

[a] 6. Rehm et al comment that the choice of the low-energy cutoff (e.g. 1 MeV in Ref. [Zi]) restricts the emission angle of the protons with respect to

the foil to a small cone representing only a few of the total solid angle. This effect seems to have been neglected in the efficiency calculations for the limits quoted by these authors.

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APPENDIX A

NEUTRON DETECTION

Neutrons from dd fusion can be detected either at their initial energy in the MeV range (fast), or after their energy has been 'moderated' by sharing it in successive collisions with light material -- particularly hydrogen. Fast neutrons can be detected by photomultiplier tubes viewing the proton recoil in plastic or liquid scintillation material. ^{10}B neutrons (those that have lost almost all their kinetic energy and are in thermal equilibrium at room temperature) are conventionally detected by the charged particles produced when the neutron is captured with high probability in the nucleus of an atom of ^{10}B (producing an alpha particle), or in a ^3He nucleus, producing a recoil proton. A noble gas, ^4He is used in the form of a proportional counter, while boron can be used either in the form of BF_3 proportional counters or in the solid form, with the boron immersed in plastic or inorganic scintillator viewed by a photomultiplier.

Additionally, neutrons can be detected after moderation by their capture in some material of very high capture cross section (such as cadmium Cd), which produces several gamma rays that may, in turn, be detected by a photomultiplier viewing a scintillation detector. Similarly, neutrons moderated in water are almost entirely captured on the protons

("radiative capture"), giving rise to a deuteron plus a gamma ray with 2.2 MeV.

Finally, moderated neutrons may be captured in a trace element in the moderator (silver is a detector of choice) to produce a radioactive material that can be transported away from the experimental apparatus and counted separately with high efficiency at low background. The emitted radiation is typically a beta ray (negative electron), or a characteristic gamma ray following the beta decay. Of course, the world has enormous experience since the 1930s in detecting neutrons and in detecting neutrons from the D + D fusion reaction.

APPENDIX B

????COULD WE DO WITHOUT THIS????

Reproduce BARC tables

Reproduce Bockris tables

APPENDIX C

CONSIDERATIONS IN TRITIUM CONCENTRATION.

Tritium is produced in the atmosphere by cosmic ray bombardment. Most of such tritium ends up in the oceans and in rivers. The "natural" abundance of tritium varies widely and was greatly increased by atmospheric testing of thermonuclear weapons in the '50s and in the early '60s. The order of magnitude of tritium in ordinary water is T/H - 10^{**-18} (1 TU). Sources vary from 1 to 200 TU. The production of heavy water from ordinary water is even more efficient in the enrichment of tritium than deuterium from the feed material. Most of the heavy water currently available is produced by the H₂S - H₂O dual temperature exchange process (GS process). The tritium content of fresh heavy water produced by the GS process is 68 dpm/ml D₂O/TU feed. Processes that are more efficient than the GS process in heavy isotope enrichment will have a minimum tritium specific activity of 50 dpm/ml D₂O/TU feed. Heavy water currently being sold on the open market has a specific activity in the range 120 - 180 dpm/ml D₂O. There are sources of D₂O with specific activity as high as 10^{**4} dpm/ml

Most of the work done to date on the search for tritium produced in the electrolysis of D₂O in cells with palladium cathodes has been done in open cells. The measurements are frequently limited to assays of the specific activities of the starting D₂O and the electrolyte after electrolysis. In general, there have been periodic additions of D₂O to replace the D₂O decomposed to form palladium hydride and D₂(gas). To determine how much tritium, if any, has been produced requires a complete inventory of the tritium at the beginning and end of the experiment. From the data on the current and on the duration of the electrolysis it is possible to estimate the amount of D₂O which has been electrolyzed. Electrolysis will enrich the tritium in the D₂O of an electrolytic cell. The amount of enrichment is primarily a function of the amount of water electrolyzed for a given type of cathode. It can reach a factor of 5 when 95% of the initial charge of water is electrolyzed. Thus a careful analysis of an electrolytic experiment must be carried out if one is to interpret specific activities of tritium after electrolysis, below 1000 dpm/ml of D₂O, as anything other than electrolytic enrichment [Bi]. f

R. Brown

Draft - Oct. 10, 1989

pp 3, 4, 5)

FUSION PRODUCTS

He^3, He^4 sets many

I. INTRODUCTION

The nuclear fusion of deuterium has been studied intensively for over 40 years. The reaction between two low energy deuterium nuclei can proceed in three ways:

- (a) $\text{D} + \text{D} \rightarrow ^3\text{He} + \text{n} + 3.269 \text{ MeV}$
- (b) $\text{D} + \text{D} \rightarrow ^3\text{H} + \text{p} + 4.037 \text{ MeV}$
- (c) $\text{D} + \text{D} \rightarrow ^4\text{He} + \text{gamma} (23.847 \text{ MeV})$

The reactions (a) and (b) have been studied down to deuteron energies of a few keV and the cross sections found to be equal to within 10%. In the interaction of deuteron beams with heavy ice or metal deuteride targets, almost one 2.45 MeV neutron is produced (with an accompanying ^3He) for every triton (with an accompanying proton). This near-equality of neutron and proton branches of the $\text{D} + \text{D}$ reaction, shown in figure 1, is a reflection of the basic symmetry of nuclear forces between proton and neutron, disturbed only slightly at the MeV energies of the emerging particles by the Coulomb interaction, which is not symmetrical between proton and neutron. The cross sections for reaction (c) are very small -- on the order of 10^7 lower than the first two.

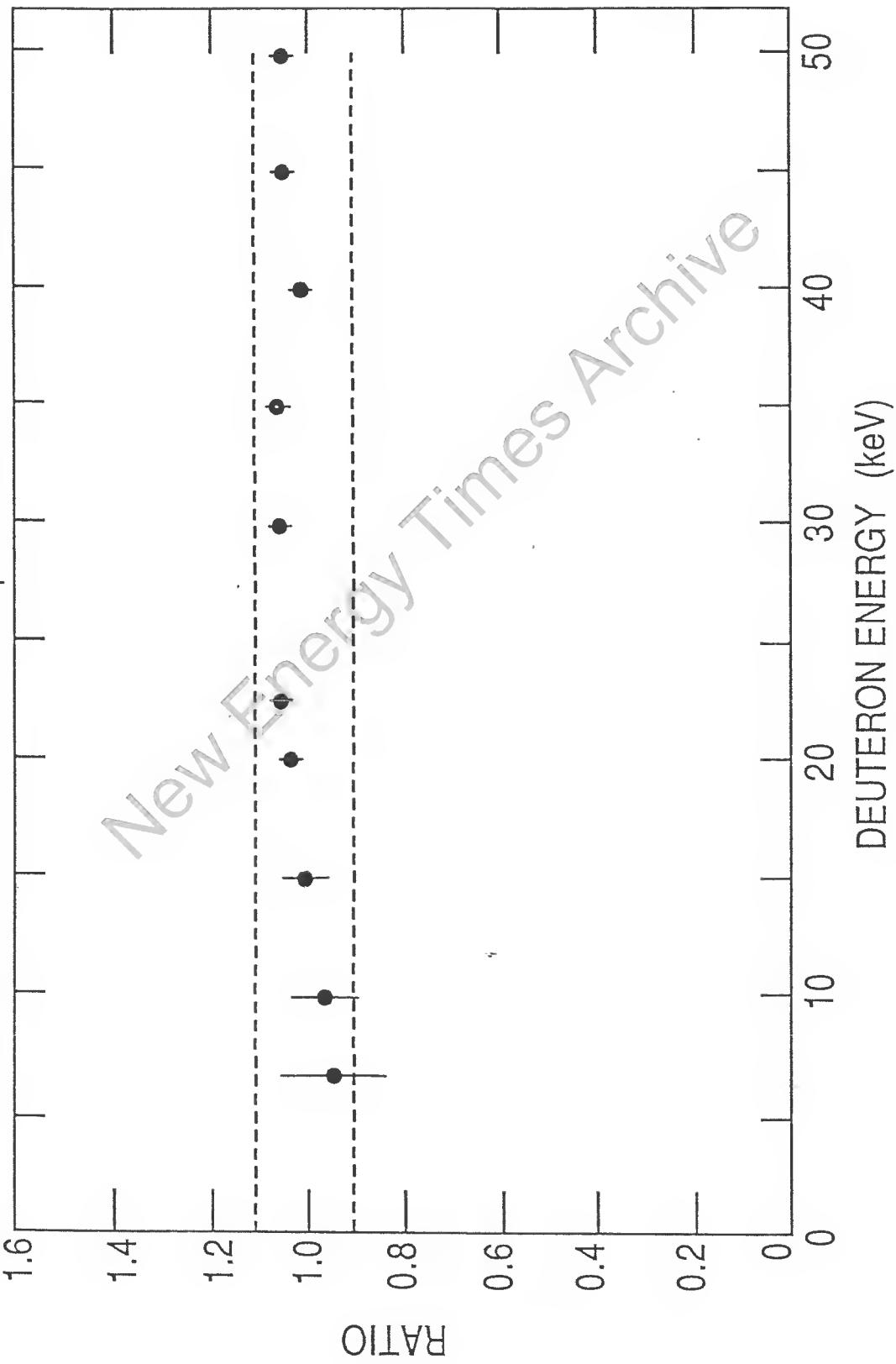
All nuclear reactions at low energies between two deuterons are retarded by the Coulomb repulsion between the positively charged nuclei -- the penetration of the repulsive Coulomb barrier changes exponentially with bombarding energy: for instance the measured cross section for reaction (b) changes from 0.2 microbarns at 2.7 keV to 35 millibarns at 100 keV. But the ratios for the three reactions appear to be constant below 100 keV.

Any fusion between deuterium nuclei must lead to detectable fusion products. For reaction (a) neutrons are the most easily detected product, by direct counting. For (b) the protons or tritons can be detected by direct counting, and the accumulated tritium could also be identified by its radioactivity, albeit with lower sensitivity. Neutron counting is perhaps again the most useful technique here, since neutrons must be produced by the energetic tritons interacting with other deuterons in the material at the rate of 1 neutron for every 10,000 to 50,000 tritons. Reaction (c) leads to readily detectable high energy gamma rays and ^4He ; the latter may be identified by mass spectroscopic measurements, whose sensitivity is low -- though the 10^{17} levels implied by 1 watt of heat should be readily observable.

In the following we summarize the experimental evidence on these fusion products. First we discuss the plausibility of reactions at room temperature and the issue of whether the constancy of the three reaction modes is a reasonable extrapolation to very low energies. Then the data on neutrons, charged particles, gamma rays and tritium are summarized. Finally, some comments are included on the more exotic explanations, and geophysical evidence is summarized on proposed cold fusion in the interior of the earth.

ANL-P-19,711

RATIO OF $^3\text{He} + \text{n}$ AND $^3\text{H} + \text{p}$ BRANCHES FROM D+D



2

Alan Budd says "Fowler" graph
shows expected dip at low energy.

Jhr Hazeij will give me
references to START work.

II. THE REACTION PROCESS

Fusion reactions can occur only if during a nuclear collision the Coulomb barrier is surmounted or, at low energies, penetrated so that the nuclei approach each other within about 10^{-12} cm. This distance is some 10000 times smaller than the typical separations of atoms in ordinary matter. The penetration of the barrier at low energies takes place through a well-understood quantum mechanical phenomenon called tunneling that allows fusion to occur in collisions far less violent than might be required otherwise.

In the thermonuclear fusion that occurs in stars and in laboratory "hot fusion" experiments, very high temperatures provide the violent collisions required to produce fusion. However, in the so-called cold fusion experiments, it is claimed that the penetration of the barrier through quantum mechanical tunneling has somehow become so effective as to allow fusion to occur even at room temperatures. Further, some of the experimenters claim that the nuclear process is changed by some unspecified mechanism so as to alter dramatically the nature of the reaction products. Each of these claims must be understood as separate and equally surprising.

Some simple calculations serve to illustrate how remarkable the claim of fusion at room temperatures really is. The fusion rate for the two deuterium nuclei in a deuterium molecule (where they are even closer than they are when embedded in a metal) results in one fusion per year in a solar mass of deuterium. Further, the fusion of protons and deuterons is 10^9 times faster than the D + D reaction claimed to have been observed (although it is still extraordinarily slow). There is no known mechanism by which these rates could be enhanced by the 40-50 orders of magnitude required to agree with the reported observations.

One commonly invoked mechanism for enhancing cold fusion rates is screening by "heavy" electrons. It is true that endowing the electron with a hypothetical mass some 5-10 times larger than it actually has would enhance fusion rates sufficiently to agree with most cold fusion claims [Ko]. It is also true that there are "heavy fermion" materials whose thermodynamic properties at very low temperatures are characteristic of quasiparticles with masses many times those of a free electron. However, this phenomenon is understood as involving long-wavelength excitations in which strong correlations "dress" electrons near the fermi surface. As such, heavy fermions extend over many lattice sites. Because the tunnelling in nuclear fusion occurs at distances smaller than one lattice site, only the short-wavelength "bare" electron excitations are relevant for screening, and cannot enhance the fusion rate significantly.

IIa. The D + D Branching Ratios.

The relative rates of reactions (a), (b), and (c) are called the branching ratios and are a crucial issue in the discussion of some cold fusion claims. These reactions have been studied in laboratory experiments using accelerators for deuteron energies above a few keV [Kr]; the smallness of both cross sections prevents reliable measurements at lower energies. The ratio between the two rates exhibits a weak energy dependence and is near 1.0 at the lowest energies as seen in figure 1. Data from muon-catalyzed D + D fusion [Bal], which probes an even lower energy range, is still consistent with nearly equal rates.

A branching ratio of more than one million would be required to explain experiments that claim to observe high fusion rates (either through heat or tritium production) without a corresponding high neutron flux. As "cold fusion" is thought to occur at energies on the order of eV, this is not directly ruled out by the data discussed above. However, there is no known mechanism for inducing such a rapid energy-dependence in the branching ratio. The Oppenheimer-Phillips process involving the Coulomb break-up of the deuteron has sometimes been invoked in this regard. However, this approximation is not valid at low energies in the D + D system.

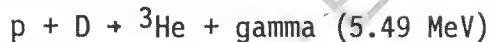
IIB. The Gamma Branch.

Some researchers have hypothesized that the $D + D \rightarrow {}^4He + \text{gamma}$ (23.847 MeV) reaction, which is ordinarily some 10^7 times weaker [Bar] than reactions (a) and (b) in which two fragments are produced, somehow dominates in cold fusion situations. To be consistent with the lack of neutrons, a very large enhancement of the gamma branch by a factor somewhere in excess of 10^{13} would be required. We know of no way whereby the atomic or chemical environment can effect such an enhancement, as this ratio is set by phenomena on a length scale some 10^4 times smaller than the atomic scale.

Even if there were such an enhancement, the absence of observed high-energy electromagnetic radiation (photons, positrons, or fast electrons) rules out such a mechanism. While direct coupling to the lattice through unspecified mechanisms has been invoked to suppress such radiation, any such coupling must occur through the electromagnetic field and would result in some observable high-energy radiation.

IIC. The p + D Reaction.

It has been suggested that an alternative fusion process could be the reaction



for which the penetration factors are still overwhelmingly small at room temperature, but somewhat less so than for the D + D process [Ko]. This reaction must produce a readily observable gamma ray and if it is to account for 1 watt of heat, then it should also produce 3He in observable concentrations.

IID. Estimate of Secondary Yields from Fusion Products.

i) **Neutrons from tritium.** The tritons produced in reaction (b) are produced with an energy of 1.01 MeV. This energy must be lost in the immediately surrounding material, which in the case of an electrolytic cell is either the Pd electrode saturated with deuterium, or heavy water. The tritons will therefore bombard the deuterium in the surrounding material. The t+d reaction is a rich source of neutrons, with a cross section that reaches 5 barns at 0.12 MeV, then falls to about 0.7 barns at 0.5 MeV, and reaches slightly below 0.3 barns at 1 MeV. For the 1.01 MeV tritons from the D + D reaction one may assume an average cross section of about 1.2 barns. For tritons that are stopped in PdD this translates into a neutron yield between 0.15 and 0.2×10^{-4} neutrons per triton;

for tritons stopping in heavy water there are about 0.9×10^{-4} per triton.

ii) Coulomb excitation of Pd by protons. The even Pd isotopes (104, 106, 108, 110) with abundances of 11, 27, 26, 12 % have first-excited 2+ states at 555, 512, 434, 374 keV and $B(E2)$ values between 0.5 and 0.8 barns. The cross sections for Coulomb excitation are in the vicinity of 20 to 50 mb and thus the yields expected are 2 to 5×10^{-6} per proton. In palladium the half thickness for absorption of these gamma rays is about 4 mm, in water it is several cm.

In terms of power, there must be about 10^8 /sec secondary neutrons per watt of fusion, even if direct neutron production is completely suppressed and all the reaction goes into tritium production. Under these conditions there must also be slightly under 10^7 secondary photons per second, of well defined energies, in the 500 keV range.

III. NEUTRONS

IIIa. Detection.

As discussed above neutrons are a major product of D + D fusion. Neutrons are very convenient particles to detect, since they interact only with the nuclei of atoms and so can emerge from reaction vessels of substantial size unscathed and without having lost any energy. Similarly, large counters can be used without the problem of thin entrance windows, since neutrons enter into the volume of the counter without difficulty. Some simple facts about neutron detection are summarized in Appendix A.

IIIb. Selection of Data.

In what follows, we have tried to use published material, where available, or material prepared for publication and presented at formal meetings or as preprints distributed without restriction as to citation. It is important to include not only positive results, that claim the detection of neutrons, but also the negative ones, that have attempted to replicate the experimental procedure of the former and failed to detect neutrons at a level of sensitivity substantially better than the positive results.

IIIc. Initial claims.

The University of Utah (UU) group in its initial publication [Fle] claimed the detection of neutrons from D + D by virtue of the gamma ray emitted by the capture of the moderated neutron in the water bath surrounding the electrolytic cells. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper. A very narrow peak in the pulse-height spectrum from the NaI scintillator was shown in the paper, considerably narrower than is possible with this type of detector, and with internal inconsistencies in the energy scale.

These very questions were taken up by a group at MIT, [Pe] who showed that the photo peak at 2.2 MeV obtained at MIT from Cf spontaneous fission neutrons moderated in water and radiatively captured on protons is accompanied by other peaks from natural background that enable one to calibrate the energy, and

Summary conclusion from top of page 8.

four points

*with natural background
to telephone or written plausibility
with extrapolation consistency*

*Latest data
submitted*

successive interchange between UU and MIT groups in the scientific literature has demonstrated that the claimed detection of neutrons by the proton capture gamma ray at UU was an artifact of the experimental apparatus.

The original publication from Brigham Young University (BYU) [Jo] presented the detection of neutrons as the sole experimental evidence for the existence of cold nuclear fusion. The neutrons were detected in a two-stage neutron counter -- first by the proton recoil in organic scintillator, followed within a few tens of microseconds by a signal from the capture of the moderated neutron on boron viewed by the same photomultipliers. This double detection of a single neutron serves substantially to reduce the ambient background due to gamma rays, although there remains background in the experiment due to gamma rays and to real neutrons from cosmic rays* and other sources. The group at BYU has chosen to attempt to vary the experimental conditions in order to obtain a greater rate of D + D fusion, and so has not presented much more data than the original paper on the detection of neutrons with that counter. In fact, BYU has been working in collaboration with other groups, notably at LANL [Me], and also with a group at Yale University. The original claim of neutron detection five standard deviations above the background is somewhat reduced in statistical strength if one considers the degrees of freedom that are fixed by the presentation of a peak in one of a number of experiments and at a particular energy, and also the possible fluctuation in the cosmic-ray neutron background. Ordinarily, however, such a result can be improved through improved shielding or by moving to an underground site.

Typical of the latter is work presented by the group at Sandia National Laboratory, [Ald] in which a site was found with substantially less background and results presented for a limit on neutrons produced in electrolytic fusion. Similar results from the Frejus tunnel in France were also presented in Santa Fe. [DeCl]

soft to coldotope rule

*Cataldo, Mark b
pmt.
bar
C-*

Many claims have been made for the production and detection of neutrons produced in electrochemical cells, but these claims have almost all been withdrawn or moderated by the discovery of difficulties with the counter -- particularly with the BF₃ counters used. In some cases, the counters are sensitive to humidity; in others to microphonic noise (vibration); or to other afflictions. A summary of some of the limits on neutron fluxes reported, compared to the flux reported by the BYU group, is shown in Table I.

IIId. Dry Fusion.

Results presented in April 1989 by a group at Frascati [DeN] opened an entirely new opportunity for the observation of D + D cold nuclear fusion. In this work, deuterium gas at 60 atmospheres pressure (60 bar) was allowed to contact titanium lathe turnings in a stainless steel reaction vessel. That allowed the temperature of the sample to be varied either by heating or by cooling. No neutrons were observed from the hydriding reaction at room temperature or at elevated temperature, when viewed by a nearby BF₃ counter.

*Additional care is needed as the rate of cosmic ray neutrons can fluctuate by 20% or more with variations in barometric pressure or with solar activity.

However, after cycling to nitrogen temperature, bursts of counts were obtained from the counter -- typically on the order of 20 counts per burst emerging over a period of 60 microseconds. One set of data was presented on counts obtained by cycling to nitrogen temperature, showing neutrons essentially only in these bursts.

A totally different type of neutron emission was also claimed by the Frascati group [DeN] following warming from nitrogen temperature over one weekend. A bell-shaped curve rising to a peak of 300 neutrons per ten-minute counting interval extended over some 5 hours. This, of course, is an important experimental result, and provoked great effort toward verification both at Frascati and elsewhere. A recent private communication from M. Martone at Frascati indicates that there has been no confirmation of either the burst results or of the continuous neutron emission from the D-Ti system or from any other dry fusion activity at Frascati. In addition, electrochemical cells operated without producing observable numbers of neutrons, and their operation was terminated during the month of July.

A group at LANL [Me] has conducted dry fusion work with Ti and Pd, and has presented results both at the Santa Fe meeting and in a preprint. This group at LANL uses high-efficiency systems that moderate any fast neutrons emitted from experimental cells, detecting the moderated thermal neutrons in ^3He gas counters. Bursts of neutron counts are sometimes observed 3000-5000 seconds after the sample is removed from liquid nitrogen, at a time when the sample temperature is typically -30 C. These bursts, consisting of about 100 neutrons at most, are seen in about 30% of the samples tested. An attempt to reproduce this effect at Sandia National Laboratory yielded entirely negative results [Ald].

At the Santa Fe workshop, Moshe Gai of Yale presented results obtained in collaboration with Brookhaven National Laboratory, in which no neutrons were detected from electrolytic cells [Ga]. [not in dry fusion section]

Finally, a conference report from the Bhabha Atomic Research Center (BARC), [Iy] provides text and tabulated results from several groups at BARC. Fig. 1 of the BARC report shows counts from neutron detectors observing a large electrolytic cells, with an estimated 2×10^7 neutrons in the 5 minutes following an overpower trip of the electrolyzer. Tritium and neutrons are observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd. Fig. 2 of the BARC report shows dry fusion ^3He counter output during gradual rise of temperature of 20 g of Ti while deuterium gas was being pumped off. It is also commented that samples could be loaded with deuterium gas at 1 bar and 900 C, and that "one such disc shaped button loaded on Friday 16th June began emitting neutrons on its own, almost 50 hours after loading. It produced (about) 10^6 neutrons over a 85-minute active phase. The background neutron counter did not show any increase in counts over this time."

IIIe. Secondary Neutron Production.

Tritium
There are severe problems of consistency between the number of tritium atoms found in some of the experiments discussed above and the number of neutrons detected. The BARC abstract reads, "The total quantity of tritium generated corresponds to about 10^{16} atoms suggesting a neutron to tritium branching ratio less than 10^{-8} in cold fusion." But, as discussed above there must be at least

*Hasn't burstein who did low power ever take a cold fusion counter
to Sandia?*

(Include all
here)

In the BBOE Experiments.

one neutron per 100,000 tritons. If the observed tritium were originating from fusion, 1000 times more than was observed!

[Ignore conclusion re tritium]
Jensen; Tech ABM,

IV. CHARGED PARTICLES AND GAMMAS

A few experiments [Po, Pr, Re, Su] to measure the 3 MeV protons and/or the 1 MeV tritons produced in the reaction, $D + D \rightarrow ^3H + p$, have been reported; they are summarized in Table II below. A variety of different methods has been used, but the lowest limit on charged-particle production appears to be that set by Price using plastic track detectors. Their setup was designed so that the light water control cell matched the heavy water cell as closely as possible. Electrolysis was performed for 13 days, and the cathode stoichiometry was determined to be $Pd(H,D)0.8$. Both cells showed track production rates that agreed and were consistent with the alpha-particle emission rate for native Pd foils due to trace (ppm) impurities of the natural ^{238}U and ^{232}Th decay chains; however, no tracks due to protons with energies between 0.2 and 3 MeV or tritons with energies between 0.2 and 1 MeV were found. From these data Price [Pr] set limits on the fusion rate of less than 0.002 per cm^3 per second. This value results in an upper limit of 8.3×10^{-26} fusions per dd pair per second. This is about an order of magnitude lower than the limits obtained using Si surface barrier (SSB) techniques.

A limit on the fusion rate of 0.028 per cm^3 per second or 1.2×10^{-24} fusions per dd pair per second was obtained by Ziegler [Zi] using a SSB technique. Porter [Po] used a SSB detector to view the back of a 76 micron thick Pd foil cathode in a heavy water electrolysis cell. They obtained a limit of less than 6×10^{-25} protons per dd pair per sec at the 2 sigma level; chemical analysis of their electrolytes showed no evidence for anomalous increases in tritium concentrations. Sundqvist et al. [Su] also used a SSB technique to detect protons. The detector was placed close to Pd foil cathodes that were thin enough to allow all the protons produced to escape from the foil. All of their runs gave a null result within the statistical errors, resulting in a fusion rate of $-2.1 (\pm 2.2) \times 10^{-24}$, if a bulk process is assumed.

Recently, Rehm [Re] has reported using a proportional counter to search for charged particles from electrolytic cells with Pd and Pt electrodes in 0.1 M LiOD in D_2O . They obtained an upper limit of 4×10^{-23} fusions per dd pair per second, not as low as the limits using the other methods.

In summary, a variety of experimental techniques has been used in searches for charged particles; all of them set very low limits on fusion occurring via the $D + D \rightarrow ^3H + p$. Most of these results set limits that are considerably less than Jones' [Jo] value of $1.00 (\pm 0.82) \times 10^{-23}$ fusions per dd pair per second for the $D + D \rightarrow ^3He + n$ channel obtained from neutron measurements. (The uncertainty was calculated by [Su]).

Sundqvist

The upper limit of Price [Pr] of 8×10^{-26} fusions per dd pair per second is much below the average low rate inferred from the neutron measurements of Jones or even those of Menlove [Me]. The extremely low limits which the searches for charged particles (either protons or tritons) place on their production is clearly inconsistent with the reported production of tritium via the cold fusion reaction.

IVa. GAMMA-RAY SEARCHES

As was mentioned above, a rare branch of the D + D reaction proceeds through capture, in which a 23 MeV gamma ray is emitted. Similarly, the p + D reaction is associated with a 5.49 MeV gamma ray. Several searches have been published in which no gamma rays that would be associated with the D + D or p + D capture reactions were seen. They include a report by Henderson [He] who cites limits around $10^{-23}/\text{sec}$ 23 MeV gamma rays emitted per deuteron in various cells. Porter [Po] reports no 5.5 MeV gamma rays -- though no absolute limit is quoted. They also comment on the absence of Pd K X-ray production. Greenwood [Gr] also report limits of 10^{-23} for gamma rays above 1.9 MeV. Other negative results are quoted in the Santa Fe abstracts without quantitative detail.

from Pd.

V. TRITIUM

As discussed above, one branch of the D + D reaction produces tritons and protons. As was also discussed, searches involving the direct detection of charged particles have yielded rather stringent negative results; so have the lack of neutrons. A number of searches have also been made for the tritium accumulated during the electrolysis of D₂O with palladium cathodes, determining tritium content by detecting the radioactive decay of tritium. In such experiments it is important to determine the initial tritium content of the heavy water and recognize the fact that the electrolysis of the heavy water will enrich the naturally occurring tritium in the heavy water.

The detection of tritium by measurement of its beta decay is inherently a less sensitive probe of the D + D reaction than the direct measurement of neutron production or charged particle production. About 10^7 tritium atoms give 1 decay by beta emission per minute. The tritium content of normal water is about 10^{-18} relative to hydrogen but, as discussed in Appendix B the normal manufacturing of heavy water also enriches in tritium and thus heavy water currently being sold gives between 120 and 180 disintegrations per minute (dpm) from tritium decay.

Va. Null Experiments.

Most of the work reported to date on the search for excess tritium produced in electrolytic cells can be accounted for by the electrolytic enrichment process. This includes the original report by Fleischmann and Pons [Fle], and experiments at ANL,[Gre,Red] BNL,[Da,McB,Wi2] Cal Tech,[Le2] CRNL,[Sc] INEL,[Lo] LLNL,[Al] NRL,[Er] ORNL,[Fu,Sc] Sandia,[Na] SRL,[Ra] Texas A & M,[Ma] and Utah.[Wad] *first null results*

Vb. Tritium Bursts.

A small number of experimenters report occasional irreproducible amounts of excess tritium in their D₂O samples taken from their electrolytic cells after days of operation. This includes observations by Storms[St] at Los Alamos, and Fuller [Fu] and Scott[Sc] at ORNL. The ORNL experiments show single cases of an excess of tritium which is of short duration, after which a cell returns to background level. Storms reports excess tritium, 100 times background, in two cells out of fifty.

Vc. Closed Cells - Correlation with Excess Heat.

Four different groups [McB, McC, Sc, Ma] have now looked for tritium production in closed electrolytic cells. These experiments detect all the tritium from the electrolytic process with the exception of that which may be contained in the Pd cathode. In general, the deuterium inventory in the cathode is negligible compared with the D₂O. Only that tritium formed within the cathode and which remains there because of slow diffusion is unaccounted for. There is no electrolytic enrichment of the tritium in the make up D₂O. In these experiments the total amount of excess tritium formed in the total D₂O is less than 10⁴ T atoms/sec. If this tritium is produced by the D + D reaction, then the maximum amount of excess power (cold fusion power) is 10⁻⁵ milliwatts. In one experiment [Wad] in an open cell there was a heat burst of 35 watts for 90 minutes (187,000 joules). The tritium was measured after the burst and no excess above the electrolytic enrichment was found. Clearly the heat burst does not come from the D + D reaction.

Vd. High Levels of Tritium.

Two groups [Pa, Iy] find tritium at levels of 10¹² to 10¹⁴ T atoms/ml D₂O after periods of electrolysis of the order of hours. This amount of tritium cannot be produced by electrochemical enrichment with the D₂O volume reductions reported. The results of the Bockris [Pa] group at Texas A & M for cells in which excess tritium was found are given in Table 1 of their paper. Excess tritium is not found in all of their cells. A listing of cells in which no excess tritium was found is given in their Table 4. The Bockris cells are 0.1 M in LiOD and have nickel anodes. They precipitate nickel oxide during the electrolysis; some nickel is also electroplated out on the palladium cathode. In one experiment, A8, the specific activity of the D₂ gas produced by the electrolysis was measured. It is 100 times that of the electrolyte.

D₂ (gas) containing tracer amounts of tritium and in equilibrium with D₂O (liquid) has a specific activity that is lower by 0.6 than the D₂O (liquid). If the tritium is formed during electrolysis, this result suggests that it is formed in the chemical species DT and that the tritium in the liquid D₂O is the result of hot atom processes or slow isotopic exchange of the DT (gas) with D₂O (liquid) [Bi2].

Wolf [Wo] at Texas A & M have looked for neutron production in Bockris type cells. An upper limit to their neutron production rate is 1 neutron/second, which is 10⁻¹⁰ times that of the tritium production rates reported with similar cells by Packham et al. [Pa]. This is a large discrepancy from the equal production rates for neutrons and tritons required by the branching ratio in the fusion reaction, discussed in section II, and is inconsistent, by a factor of 10,000 to 100,000, even with the secondary neutrons that must accompany the tritons produced from nuclear fusion. One is strongly inclined to conclude that the excess tritium found in the electrochemical cells cannot be the result of nuclear fusion in the cell. *Bockris*

The most extensive and systematic search for tritium in the electrolysis of D₂O with Pd cathodes has been carried out by Martin [Ma] at Texas A & M. He has used both open and closed cells. His cathodes come from either Johnson & Mathey, a major supplier, or Hoover and Strong, who supplied the cathodes to the Bockris [Pa] group. He has operated cells with Pt, Ni wire and Ni gauze

J. Bockris
et al.
expt.

??

[Alem Barj] on 10/06/89 are
 out 14 cells found 2×10^5 dyn/cm²
 $\approx 10^6$ in 66 sec, but in 100 sec,

(obtained from Bockris) anodes. In none of his cells does he find any excess tritium beyond that expected from electrolytic enrichment. Nor does he find any neutrons. Two of his cells produced excess heat but no tritium. In short, he has been unable to reproduce the results of the Bockris group.

The BARC [Iy] group have found amounts of tritium comparable to the Bockris group in the D₂O electrolyte from cells in which electrolysis was carried out for a few days with currents varying between 1 to 100 amperes. As was already mentioned above, here there is again a factor of 1000 internal inconsistency between their measured neutron yields and the neutrons that have to be there if this tritium was indeed produced by fusion -- even if one assumes the very unlikely drastic modification of the branching ratio in the D + D reaction.

The experiments carried out to date include the large number of null experiments. There are a few experiments in which excess tritium is found, and which other groups have not been able to reproduce. These measurements also contain a serious internal inconsistency, in that the ratio of measured neutrons to tritium is smaller by orders of magnitude than what is consistent with a fusion process being their source. Additional investigations are desirable to clarify the origin of the excess tritium that is occasionally observed.

Novel

VI. EXOTIC EXPLANATIONS

Note

The data on fusion products, even where positive results are reported, give rates far below those that would be expected from the levels of heat reported in some electrolysis experiments. There have been some attempts to propose mechanisms where the reaction heat from the D + D → ⁴He process would go entirely into lattice heat, rather than a photon [Wal, Ha]. Analogies have been made with the internal conversion process, and with the Mossbauer effect. Neither of these analogies is applicable to ⁴He.

Internal conversion allows an atomic electron of an excited nucleus to carry off the reaction instead of a photon. This process is understood quantitatively -- it is dominant in heavy atoms with tightly bound inner electrons and for low energy (less than 1 MeV) photons. In helium the atomic electrons are loosely bound and the photon is 23.8 MeV -- there can not be any appreciable coupling between the photon and the atomic electrons, and internal conversion or any related process cannot take place at anywhere near the rate that would be required.

To convert
by γ ray
latt.
energy
He³
He⁴

In the Mossbauer effect the momentum of a very low energy (below 100 keV) photon is taken up by the entire lattice in a coherent mode, but not its energy. The process cannot be relevant to the present process.

all
3 He points
with

Considering experimental evidence more generally, there have been careful studies of a very large number of reactions analogous to the D + D fusion process, in which gamma rays of comparable energy emitted from low-energy nuclear reactions (thermal-neutron capture gamma rays) and the cross sections for capture have been studied very carefully and quantitatively. Their knowledge is essential to the operation of fission reactors. If there were any anomalous processes in which the energy of a capture gamma ray were converted into lattice heat, this would have almost certainly been noticed as a discrepancy in cross sections with major implications for the operation of reactors. After four decades of extensive study of the processes relevant to

check
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the operation of fission reactors the possibility is extremely remote that an entirely new process, that could dominate these nuclear reactions, would have remained hidden.

VII. SEARCH FOR PRODUCTS OF COLD FUSION IN THE EARTH

Products of low-level cold fusion have been inferred to be produced by natural geologic processes [Jo, Jo1]. The $^3\text{He} : ^4\text{He}$ ratio is anomalously high in volatiles from deep-source volcanoes such as Hawaii, Iceland, and Yellowstone [Cr, Ku, Mam]; anomalous ^3H is also suggested by fragmentary data [Om, Jo2], and production of other radiogenic products such as ^{36}Cl have been predicted [Pk]. Although the high ^3He values have previously been considered relict from early earth processes, presence of anomalous ^3H or ^{36}Cl (beyond that due to bomb tests) would be definitive evidence of natural cold fusion at depth within the earth. Implications would be major for geophysical problems such as heat-flow modelling, element-distribution with depth, and composition of the Earth's core.

Although some ~~knowledgeable~~ isotope geochemists see no evidence for naturally occurring cold fusion [Cr1], several government and university labs are searching for evidence of such fusion processes as recorded by volcanic volatiles [Jo2, Ky, Go, Loc, Qu]. Even if laboratory experiments for cold fusion are discredited, such geologic studies could add much to understanding of the behavior of volcanic volatiles. No rigorous results are yet available, but experiments proposed or underway at Brigham Young, Los Alamos, Lawrence Livermore, New Mexico Tech, and the U.S. Geological Survey (Denver) should yield data within 6 months to 1 year.

VIII. SUMMARY

A number of careful experiments have been carried out to search for the expected products of cold fusion. None have seen these products at anywhere near the level that would be expected from the heat production reported in electrolysis, by many orders of magnitude. Some experiments report neutrons or tritium at a much lower level -- however, the rates of these two fusion products (measured in the same experiments) are inconsistent with each other, again by large factors.

The neutron bursts reported in some experiments also suffer from not being reproducible by other experimenters. While it is conceivable that some mechanism might produce very small bursts of hot fusion (e.g. high voltage internal sparks associated with fracture of the material at certain temperatures), at the present time the experimental evidence is not readily reproducible, and if real, the phenomenon does not appear to be related to "cold fusion" as postulated in the heat production experiments.

If there were such a process as room temperature fusion, it would require not only

- (a) the circumvention of fundamental quantum mechanical principles, which have been carefully tested against numerous measurements of barrier penetration (such as the systematics of spontaneous fission and alpha radioactivity lifetimes and those of nuclear cross sections), but also

- (b) drastic modifications of branching ratios in the D + D reaction, and
- (c) the invention of an entirely new nuclear reaction process.

A quotation from Lewis Carroll seems appropriate:

'Alice laughed. "There's no use trying," she said: "one can't believe impossible things."

"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

parme

New Energy Times Archive

maybe 4 watt

TABLE I. SOME COLD FUSION NEUTRON RATES

Authors	Reference	Neutrons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
<i>Yield corresponding to 1 watt of heat production</i>	<i>[Fle]</i>	3×10^{-11}	3×10^{12}
<i>Yield corresponding to neutron yield of Jones et al</i>	<i>[Jo]</i>	10^{-23} [b]	¹
Broer et al	[Br]	$< 2.2 \times 10^{-24}$	< 0.2
Williams et al	[Wi]		< 0.2
Lewis et al	[Le]	$< 1.5 \times 10^{-24}$	$< .15$
Alber et al	[Alb]	$< 5 \times 10^{-25}$	< 0.05
Gai et al	[Ga]	$< 2 \times 10^{-25}$	< 0.02
Schriber et al	[Schr]		< 0.02
Kashy et al	[Ka]	$< 10^{-25}$	< 0.01
De Clais et al	[DeCl]		< 0.01 < 0.001

[a] assuming that neutrons are produced throughout the volume of Pd.

[b] At 50% Fe, report from ?? later (John Heijboer) ~~as counts~~

*Please repeat their results with the
forwards refer to the discovery.*

TABLE II. SOME COLD FUSION FAST CHARGED PARTICLE RATES

Authors	Reference	Protons per DD pair per sec [a]	Yield Normalized to Jones et al. neutrons
Yield corresponding to 1 watt of heat production [File]		3×10^{-12}	3×10^{12}
Jones et al.	[Jo]	1×10^{-23}	1.0
Rehm et al.	[Reh]	$< 4 \times 10^{-23}$	< 4
Schrieder et al.	[Schr]	$< 3.1 \times 10^{-24}$	< 0.31 [b]
Sundquist et al.	[Su]	$< 2 \times 10^{-24}$	< 0.2
Ziegler et al.	[Zi]	$< 1.2 \times 10^{-24}$	< 0.12 [b]
Porter et al.	[Po]	$< 6.7 \times 10^{-25}$	< 0.07
Price et al.	[Pr]	$< 8.3 \times 10^{-26}$	< 0.008

[a] assuming that particles are produced throughout the volume of Pd and detected from a thickness capsule with the range of the charged particle.

[b] 6. Rehm et al comment that the choice of the low-energy cutoff (e.g. 1 MeV in Ref. [Zi]) restricts the emission angle of the protons with respect to the foil to a small cone representing only a few of the total solid angle. This effect seems to have been neglected in the efficiency calculations for the limits quoted by these authors.

Normal only -- Fe capsule -

3-letter refs., with year, and a,b,c.

16

[Alb 1989]

all authors
priv. communication

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APPENDIX A

NEUTRON DETECTION.

Neutrons from dd fusion can be detected either at their initial energy in the MeV range as "fast" neutrons, or their energy has been "moderated" by sharing it in successive collisions with light material -- particularly hydrogen. Fast neutrons can be detected by photomultiplier tubes viewing the proton recoil in plastic or liquid scintillation material. Slow neutrons (those that have lost almost all their kinetic energy and are in thermal equilibrium at room temperature) are conventionally detected by the charged particles produced when the neutron is captured with high probability in the nucleus of an atom of ^{10}B (producing an alpha particle), or in a ^3He nucleus, producing a recoil proton. A noble gas, ^3He is used in the form of a proportional counter, while boron can be used either in the form of BF_3 proportional counters or in the solid form, with the boron immersed in plastic or inorganic scintillator viewed by a photomultiplier.

Additionally, neutrons can be detected after moderation by their capture in some material of very high capture cross section (such as cadmium Cd), which produces several gamma rays that may, in turn, be detected by a photomultiplier viewing a scintillation detector. Similarly, neutrons moderated in water are almost entirely captured on the protons ("radiative capture"), giving rise to a deuteron plus a gamma ray with 2.2 MeV.

Finally, moderated neutrons may be captured in a trace element in the moderator (silver is a detector of choice) to produce a radioactive material that can be transported away from the experimental apparatus and counted separately with high efficiency at low background. The emitted radiation is typically a beta ray (negative electron), or a characteristic gamma ray following the beta decay. Of course, the world has enormous experience since the 1930s in detecting neutrons and in detecting neutrons from the D + D fusion reaction.

APPENDIX B

CONSIDERATIONS IN TRITIUM CONCENTRATIONS.

Tritium is produced in the atmosphere by cosmic ray bombardment. Most of such tritium ends up in the oceans and in rivers. The "natural" abundance of tritium varies widely and was greatly increased by atmospheric testing of thermonuclear weapons in the '50s and in the early '60s. The order of magnitude of tritium in ordinary water is $\text{T/H} - 10^{-18}$ (1 TU). Sources vary from 1 to 200 TU. The production of heavy water from ordinary water is even more efficient in the enrichment of tritium than deuterium from the feed material. Most of the heavy water currently available is produced by the $\text{H}_2\text{S} - \text{H}_2\text{O}$ dual temperature exchange process (GS process). The tritium content of fresh heavy water produced by the GS process is 68 dpm/ml $\text{D}_2\text{O}/\text{TU}$ feed. Processes that are more efficient than the GS process in heavy isotope enrichment will have a minimum tritium specific activity of 50 dpm/ml $\text{D}_2\text{O}/\text{TU}$ feed. Heavy water currently being sold on the open market has a specific activity in the range 120 - 180 dpm/ml D_2O . There are sources of D_2O with specific activity as high as 10^4 dpm/ml.

Most of the work done to date on the search for tritium produced in the electrolysis of D₂O in cells with palladium cathodes has been done in open cells. The measurements are frequently limited to assays of the specific activities of the starting D₂O and the electrolyte after electrolysis. In general, there have been periodic additions of D₂O to replace the D₂O decomposed to form palladium hydride and D₂(gas). To determine how much tritium, if any, has been produced requires a complete inventory of the tritium at the beginning and end of the experiment. From the data on the current and on the duration of the electrolysis it is possible to estimate the amount of D₂O which has been electrolyzed. Electrolysis will enrich the tritium in the D₂O of an electrolytic cell. The amount of enrichment is primarily a function of the amount of water electrolyzed for a given type of cathode. It can reach a factor of 5 when 95% of the initial charge of water is electrolyzed. Thus a careful analysis of an electrolytic experiment must be carried out if one is to interpret specific activities of tritium after electrolysis, below 1000 dpm/ml of D₂O, as anything other than electrolytic enrichment [Bi].

Date: 10 October 1989, 15:40:17 EDT
From: (R.L.Garwin (914) 945-2555) RLG2 at YKTVMV
IBM Fellow and Science Advisor to the Director of Research
P.O. Box 218
Yorktown Hts, NY 10598
To: DROMCD at CERNVM
Subject: Progress?
Reply-To: RLG2 at WATSON

I suggest seriously that you will be in an excellent situation to write a book on the Cold Fusion Caper.

I have just talked with P.K. Iyengar yesterday, who assures me that BARC still sees neutrons and tritium, but with 10^{**-8} as many neutrons as tritons. Confronted with the 10^{**-5} to 10^{**-4} yield of 14-MeV neutrons expected from 1.0 MeV Ts born in TiD or D2O, he invokes "channeling" or something to suppress them. But BARC is the most credible evidence.

I have a paper from Mol, BELGIUM (A. Bruggeman, et al) showing large "excess heat" from oscillation of the feedback circuit controlling electrolysis current, just as I suggested in my Santa Fe talk.

Dokl. Akad. Nauk SSSR Vol 307, pp99-101 (July 1989) has a paper by P.I. Golubnichii, et al, advocating cracking as a means of accelerating D for fusion. Not persuasive. But pp. 369-370 is quite exciting (M.A. Yaroslavskii) in presenting "Neutron Emission During Plastic Deformation of Deuterium-containing Solids Under Pressure." He twists the anvils of a press at liquid N₂ temperature and finds bursts of thousands of counts in a neutron counter.

I'll send you the Mol paper and the translations of Doklady (by Don McNeill, Princeton).

Dick Garwin

John Noel?

Richard L. Garwin
IBM Research Division
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October 10, 1989
(Via FAX to 9-(202) 586-3119)

Dr. William L. Woodard
Cold Fusion Panel Secretary
Energy Research Advisory Board
to the
United States Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585

Dear Bill,

This is to record a telephone conversation 10/09/89 with P.K. Iyengar, author of the July 1989 BARC report to the Karlsruhe Conference, which I have previously distributed, as I have my outgoing Telex to him of 09/07/89 and his reply of 09/13/89. Iyengar has been in the United States recently, and called me from Brookhaven. I had two conversations with him.

Iyengar says that various groups at BARC continue to detect tritium and neutrons, as indicated in the initial report. The complete report is in draft form, and he is leaving his only copy with Martin Blume of BNL, who will send me a copy. We may refer to the draft report in our ERAB final report.

Iyengar says the BARC experiments are distinguished from experiments at other laboratories by being the "only experiments with very large surface area." I pointed out to him that his Table reports results from small cells as well, which he says continue to be obtained.

He says they have "even reconditioned electrodes which no longer give neutrons, by heating them to 900 C in vacuum. After evacuating at high temperature, these electrodes once again produce tritium in electrolytic cells."

Iyengar volunteers that they continue to produce 10^{**8} times more T than neutrons and that autoradiography still shows tritium concentrations. He has just seen the 1978 Soviet paper (referred to by Steve Jones) which shows pockets of He-3 in metals, which Iyengar takes to be the product of tritium decay.

Iyengar confirms that neutrons and tritium have been obtained at BARC from cathodes made of AgPd or all Pd.

I asked him how one can imagine "10**8 times less neutrons than T," in view of the fact that the 1-MeV triton from d-d is expected to give between 1000 and 10,000 times as many neutrons simply from t-d reactions either in the metal deuteride or in the heavy water. Iyengar volunteers that this might be some kind of channeling, with the reactions from a t born in the lattice being somehow "different" from those in a beam.

Of course, I do not accept this conjecture.

Sincerely yours,

Richard L. Garwin

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→ A.J.Bard P.2 } done



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R. L. Garrett

October 10, 1989

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Dear John and Norman:

Enclosed is a rather rough draft of the revised section on calorimetry and an appendix. The subpanel members have not yet gone over this, but I hope to have their comments, revisions, etc., by the time the panel meets on October 13.

Best wishes,

Al

Allen J. Bard
Hackerman/Welch Regents Chair

bt
xc: B. Woodard

COLD FUSION PANEL REPORT

CALORIMETRY AND EXCESS HEAT

The claim for electrochemically charged palladium cells as prospective energy sources rests on reports by several groups of "excess heat" (or, more precisely, excess power) that cannot be accounted for in the thermal balance normally applied to water electrolysis. A number of other groups that have carried out careful calorimetric experiments in similar cells under a wide variety of conditions have found no excess heat. The reports considered by the Panel are summarized in Appendix , part D. Among the issues the Panel addressed in examining published reports, assessing private communications, and in site visits were whether the power levels themselves are being accurately measured and whether the reactions being considered in these cells are, in fact, satisfying the chemical assumptions made. These heat measurements have been done with calorimetry that varied as to technique and to levels of precision and accuracy. In most cases calorimetric effects attributable to excess heat are small. The calorimetric measurements are difficult to make and are subject to subtle errors arising from various experimental problems.

For the purposes of this report, the calorimetry is usefully differentiated as to whether the D_2 and O_2 gases are allowed to exit the cell completely unreacted (open cells) or are intentionally catalytically recombined to regenerate D_2O and to recover the corresponding heat (closed cells). In the case of open cells, where the gases are assumed to be vented without reaction, any output power (as heat) greater than the electrical input power minus the power equivalent of the D_2O formation enthalpy [1.527 V (volts) x I (cell current)] is considered excess, a result reported by several groups. In closed cells with total recombination (and with a deuterium-charged Pd electrode), the total electrical power in and total heat power out would normally balance (as for Pt and Pd electrodes in light water). At present, most experimenters who have performed calorimetry with closed cells under strict recombination conditions have reported no excess heat. Another important point is that most of the reported measurements that report excess heat are actually power measurements, and the data have not conclusively demonstrated that the total amount of energy produced (as heat and chemical energy) integrated over the whole period of cell operation exceeds the total electrical energy input.

Since the claimed excess heats have, in most cases, been of a magnitude significantly less than the $1.527\text{ V} \times I$ factor itself, issues of calibration, reliability, and support of the assumptions of zero recombination in open cells are especially critical. The Panel's site visits have identified experimental uncertainties, e.g., nonlinearities of the calibration in power output vs. temperature, time dependence of calibration, and doubtful accuracy of data acquisition relative to the magnitude of the effects asserted. Even in laboratories that report excess heat, this effect, under apparently identical conditions, is not reproducible. Moreover, in cases where groups reporting excess heat have supplied complete cells or materials to other laboratories, excess heat effects have not been confirmed. In none of our visits to the different sites did we see an operating cell that was actually producing excess heat. After assessing the reports from the different laboratories, considering the experimental difficulties and calibration problems, as well as a lack of consistency and reproducibility in observation of the

*Closed to be
for experiments of long duration,
at that time.*

OCT 10 '89 14:56 ALLEN J. BARD (512)471-0088

Page two

excess heat phenomenon, we do not feel that the steady production of excess heat has been convincingly demonstrated.

However, there are reports of sporadic temperature "excursions" or "bursts" that apparently represent power outputs significantly larger than the input power. These events cannot be attributed to problems with accuracy or calibration alone and are presently not understood (see Appendix E).

Refer to Mol

Appendix - Calorimetry and Excess Heat Measurements

A. Chronology

March 23-28, 1989 A press release from the University of Utah announced that "A Simple Experiment Results in Sustained Nuclear Fusion..." Statements in the release included that "the discovery will be relatively easy to make into a useable technology for generating heat and power," that "this generation of heat continues over long periods and is so large that it can only be attributed to a nuclear process."

Follow-up news stories quoted Fleischmann and Pons that they had "achieved nuclear fusion in a test cell simple enough to be built in a small chemistry laboratory," and that "the experiment generated a great deal of heat as well as neutron radiation." (NYT, 3-24). It was also reported that "they have run the device for periods as long as 100 hours and continue to produce more energy than it took to run the experiment." (Dallas Times-Herald, 3-24) and that "a palladium wire only a quarter-inch in diameter and an inch long reached the boiling point of water within a few minutes. He [Pons] said the wire produced about 26 watts of energy per cubic centimeter of wire, 'about 4 and one-half times what we put into it.'" "He [Pons] said that in an early stage of the experiments the apparatus suddenly heated up to an estimated 5000 degrees, destroying a laboratory hood and burning a four-inch-deep hole in the concrete floor." (WSJ, 3-27). "Evidence that fusion was taking place was the fact that in addition to heat they detected the production of neutrons, tritium, and helium-the expected by-products of fusion reactions." (WSJ 3-24).

James Brophy, vice president for research at the University of Utah said that "the experiment is easy to carry out once you know how. They [F & P] have reproduced it a dozen times." (Austin American-Statesman, 3-28). "The process, he [Pons] said, is extremely slow, especially if a large cathode is used. Using a cathode consisting of palladium wire, the process required 10 hours before fusion was observed. (NYT, 3-28).

April 10, 1989. A paper by M. Fleischmann, S. Pons, and M. Hawkins appears (J. Electroanal. Chem., 261, 301 (1989)). Some

details of the calorimetric measurements are given (e.g., open cell, isothermal calorimeter). Excess heat production of 5 to 111 % reported for current densities of 8, 64, and 512 mA/cm². "Enthalpy generation can exceed 10 W/cm³ of the palladium electrode; this is maintained for experiment times in excess of 120 h, during which typically heat in excess of 4 MJ/cm³ of electrode volume was liberated."

April 11, 1989. A group at Texas A & M University (C. R. Martin, B. E. Gammon, and K. N. Marsh) announce confirmation of the excess heat results from isothermal heat leak calorimeter measurements with an open cell. Excess energies of 20 to 80 % are reported (NYT, 4-11; Austin AS, 4-11). (These results were retracted by the group during a visit of panel members to Texas A & M University on 6-19-89).

April 12-30, 1989. Several other calorimetric experiments announcing excess heat appear (Appleby, Srinivasan, Texas A&M, Austin AS, 4-22; Huggins et al, Stanford, Nature, 4-27) while other groups report no excess heat.

May 1, 1989. A paper presented at the American Physical Society meeting in Baltimore reports no excess heat in calorimetric measurements with an open cell at current densities of 72 to 140 mA/cm² (e.g., N. Lewis et al, Caltech).

May 9, 1989. Several papers at the Electrochemical Society Meeting in Los Angeles report calorimetry confirming excess heat (Srinivasan, Huggins, Landau) and the first announcement of an energy "burst" that generated 4.2 MJ over a 2-day run (50 times the electrical energy put into the cell) (Fleischmann and Pons). (Science, 5-12).

May 23-25, 1989 A number of papers on calorimetry are presented at a Workshop on Cold Fusion in Santa Fe under the sponsorship of Los Alamos National Laboratory. Both positive excess heat results (Texas A&M, Stanford) and negative results (Caltech, MIT, Argonne National Laboratory, Naval Weapons Center, EG&G Idaho, University of British Columbia, Chalk River Nuclear

Laboratories). (These results, as well as some which have appeared later, are summarized in Part D). No lectures describe energy "bursts".

B. Types of Calorimeters Employed in Studies

1. Isothermal (isoperibolic or heat leak). The cell is immersed in a constant temperature bath (at T_b), sometimes separated from it by a vacuum jacket or other material to control the rate of heat conduction from the cell to the bath. The temperature of the the cell, T_c , which is always at a higher temperature than the bath, is monitored.

Type A. The heat flow from the cell to the bath is determined from the temperature difference, $T_c - T_b$, and the heat transfer coefficient, determined by periodically calibrating the cell with an internal heater in the cell, by Newton's law of cooling. In this type of cell, T_c varies and increases as the power output of the cell increases.

Type B. The cell is maintained at a constant temperature by varying the power to the heater (heat substitution method). The cell is first brought to a given steady state temperature, T_c , by the heater operating at a given power, P_h . The electrolysis cell is then turned on and the heater power decreased to a level, P_{hc} , to maintain the cell temperature at T_c . The power generated by the electrolysis is calculated as $P_c = P_h - P_{hc}$.

2. Isothermal, heat flow. (Type C). Power that flows between the cell and the external constant temperature bath is detected by a multitude of thermocouples connected in series and completely surrounding the cell chamber. The system is calibrated at different power levels by a heater in the cell chamber.

3. Flow Calorimeter. The cell is surrounded by a chamber cooled by a constant flow of water or other fluid. The inlet temperature of the fluid, T_{in} , and the outlet temperature, T_{out} , is monitored and the power evolved in the cell calculated from the difference in temperatures, the flow rate, and the heat capacity of the fluid.

C. Difficulties in Calorimetric Measurements of Power Output of Electrochemical Cells.

It now appears apparent that, in contrast to the early statements made concerning the determination of excess power in cells of the type employed in cold fusion experiments: (1) precise and accurate calorimetric determinations of power outputs of the electrochemical cells is quite difficult and subject to a variety of systematic errors, particularly with open cells; (2) the excess power levels, reported by those who find such results, are usually 2 to 30% of the input power and not factors of two or more larger than the input power.

(To be completed by L. Faulkner)

E. Heat Bursts

F. Conclusions (?)

D. SUMMARY OF CALORIMETRIC RESULTS

A. Published reports, manuscripts submitted or in press.

Research Group	Calorimeter, Cell	Pd type source	Current Density, Voltage	Results	Controls	Comments References
GROUPS OBSERVING EXCESS HEAT						
1. Univ. of Utah Fleischmann, Pons et al.	ISO A open	JM rod, sheet, cube	8, 64, 512 mA/cm ² 3-10 V	5-111 % (9)	none	n, t, γ , [1]
2. Texas A&M Univ. Appleby, Srinivasan et al.	ISO-HF (Tronac) open (s.s.)	Alfa wire	0.3, 0.6, 1.0 A/cm ² 3.4-5.6 V	6-30 %	H ₂ O Pt	[2]
3. Stanford Univ. Huggins, Gür et al.	ISO A open	disks (arc melted)	10-1000 mA 3-15 V	10-30 %	H ₂ O	[3]
4. Texas A&M Univ. Bockris et al.	ISO A	H&S rods (Ni anode)	100-500 mA/cm ²	5-25 % (3 of 10)	Pt	[4]

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D. SUMMARY OF CALORIMETRIC RESULTS

A. Published reports, manuscripts submitted or in press.

Research Group	Calorimeter, Cell	Pd type source	Current Density, Voltage	Results	Controls	Comments References
<u>GROUPS NOT OBSERVING EXCESS HEAT</u>						
1. U. British Columbia Hayden et al.	Flow closed	Englehard bars	to 2.2 A/cm ²	none (10 d)	Pt	[1]
2. M.I.T. Wrighton et al.	ISO B open	JM/Aesar rods	69 mA/cm ² 2.9 V	none (> 200 h)	H ₂ O	no t, n [2]
3. Caltech Lewis et al.	ISO B ISO C (Tronac) open	several rods	72-140 mA/cm ²	none (5)	H ₂ O	no t, n, He [3]
4. Naval Weapons Ctr. Miles et al.	ISO open	JM/Wesgo rods	100-200 mA/cm ² 3-5 V	none (1-10 d)	Pt H ₂ O	no n,γ [4]
5. Sandia N.L. Roth et al.	ISO A open	rod & Pd/Li alloy	320 mA/cm ²	none (17, 36 d)		no n, t [5]
6. AT&T Bell Labs Fleming, Law et al.	ISO C (Setaram) closed&open	several wire, rod	16-512 mA/cm ² 2-10 V	none (1-40 d)	Pt H ₂ O	[6]
7. Argonne N.L. Redey et al.	ISO B, ISO C open	JM rod	15-500 mA/cm ²	none (460 h)	H ₂ O	[7]
8. Free U. Berlin Kreysa et al.	ISO A open	rod, sheet	1.2 A 9 V	none (10 ?)	H ₂ O	no n,t,γ [8]
9. EG&G Idaho Longhurst et al.	ISO A ISO C open	foil, wire	0.1 ma-5.7 A 3.3-5.1 V	none (> 20 cells) (120 h)	H ₂ O	no n,t,γ [9]
10. Iowa St. U. Hill et al.	open	rod	0.7-1 A/cm ²	none		no n,γ [10]
11. U. Newcastle-upon-Tyne Armstrong et al.	flow open	sheet cube	100 mA/cm ² 15-20 V	none (8 d) (2)	Pt(H ₂ O)	[11]

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Part C. Appendix - Calorimetry...

EXPERIMENTAL PROBLEMS IN THE EVALUATION OF HEAT EFFECTS

The attached table summarizes many experimental efforts aimed at verification of the excess heats originally reported by Pons and Fleischmann. The Panel is aware of other efforts that have remained unreported. It has not been possible to visit all of the laboratories represented in the Table, but the Panel did send representatives to the Pons-Fleischmann laboratory and the Wadsworth laboratory at the University of Utah, the Huggins laboratory at Stanford University, the Lewis laboratory at Caltech, the Appleby, Martin, and Bockris laboratories at Texas A&M, and the McKubre laboratory at SRI International. In addition, detailed queries were made of other investigators by telephone or by conversation at meetings. It is not practical here to provide a detailed critique of each group's work. Instead, we will provide a summary of the kinds of experimental problems that we identified in the calorimetric measurements.

Since the revolutionary idea advanced in the earliest reports of cold fusion is that there is heat arising from a previously unrecognized source, the burden of proof is on those who claim to have demonstrated the effect. Accordingly, it was the Panel's responsibility to evaluate experimental work from the positive claimants with the greatest care. The experimental shortcomings discussed here were widely encountered. No single study was compromised by all of them, but no positive report that we were able to study in detail was free of such problems. For these reasons, the Panel remains unpersuaded that the excess heat effect actually exists.

1. Basic Approach

The experimental schemes used in most laboratories reporting positive heat effects normally have many elements in common. A cell containing a Pd cathode and a Pt anode immersed in D₂O (or H₂O) containing LiOD (or LiOH) is allowed to pass a steady current for long period of time. The cell body is immersed in a heat sink (usually a water bath), and precise measurements are made of the temperature difference between the interior of the cell and the heat sink. Thermocouples and microvoltmeters are usually used for the temperature measurements, but sometimes thermistors are employed. The evolved heat power is usually calculated from the temperature differential by a heat transfer coefficient, which is obtained by calibration via the input of additional heat power at a resistor immersed in the working solution.

*It is also assumed that the
apparently steady currents and voltages
do not have a superimposed alternating*

The claims of excess heat rest upon a comparison between the measured heat power evolved from the cell and the electrical power input. The latter quantity is precisely determinable as the product of the current through the cell and the voltage across it, both readily measured at four significant figures. Comparisons normally involve a correction of this quantity by subtraction of 1.54 V times the cell current, to account for the enthalpy leaving the cell as vented D₂ and O₂. The underlying assumption is that 100% of the current goes to produce D₂ and O₂, which is vented perfectly. It is possible to operate the cell in a closed fashion by including a catalytic recombiner capable of regenerating deuterium oxide from D₂ and O₂. Very rarely has excess heat been reported from such a cell.

2. Intrinsic Problems with Calibration

The calibration method used by most groups reporting positive results is based on the temporary addition of a power increment via a resistive element in the cell. This ΔP causes a change in the steady-state temperature by an amount ΔT, then a differential heat transfer coefficient k_D = ΔP/ΔT is calculated. This measurement can be carried out as the cell is running. The resistive power increment is added on top of that from the electrolytic process, thus maintaining similar stirring conditions for power dissipation. Once k_D is determined, the heat power evolved from the electrochemical action is calculated as the product of k_D and the difference in temperature between the operating cell (with the calibration heater off) and the external sink. This temperature differential sometimes reaches 30° or more, but this could develop either from excess heat or from high input current densities leading to large resistive power dissipations in the solution.

In principle and in practice, the differential coefficient k_D depends on the magnitude of the difference in temperature between bath and cell. In using the value of k_D at the operating point to calculate the evolved heat power, investigators often assume that k_D remains constant over the range of cell temperatures from the value of the bath to the operating point. The real need is for the integral heat transfer coefficient k_I at the operating temperature T_C, which is truly related to the evolved heat power P as k_I(T_C-T_B), where T_B is the bath temperature. The differential value k_D is related to k_I as:

$$k_D = \int_{T_B}^{T_C} k_D dT / \int_{T_B}^{T_C} dT$$

*in at least one case to
be a source of important
Source of error. [MOL]*

Some groups use small added heats, relative to the electrolytic power, and a single point calibration. Others use values 20-100 times as large as the reported excess heat. In these latter cases, the calibration is approximately a measurement of the integral heat transfer coefficient for a wide span of power above the operating point. This value is then assumed it to be equal to the integral heat transfer coefficient below the operating point.

In all its variants, this calibration method is intrinsically prone to overestimate the evolved heat power, because the temperature differential is typically a nonlinear function of heat power in such a manner as to produce a positive error in the estimated k_I (taken as measured k_P). An error of a few percent in the assumption that $k_I = k_P$ would invalidate nearly all reports of excess heat.

The methodology is, in principle, capable of defining the evolved heat accurately. Calibration needs to be done frequently enough over the operating range to be able to calculate k_I directly; however the Panel saw no instance in which calibrations were made in sufficient detail to allow the calculation of a true k_I .

3. Lack of Statistical Estimates of Precision

A surprising aspect of the calorimetry related to cold fusion is the lack of attention that has been given so generally to the statistical assessment of errors in the measurements. It is evident on the face of the data in some reports that a group's claim of excess heat is not supported with results of sufficient precision to allow such a conclusion. More usually, it is not possible to assess precision from reported results. In fact, the issue of precision has usually been addressed no more than cursorily, if at all, by the reporting group. Conclusions in this arena simply cannot be accepted without a thorough assessment of the measurement errors. In its visits and conversations, the members of the Panel were struck repeatedly by the absence of critical assessments of this kind. The frequency of failure on this point can be construed as an indictment of the quality of education in the experimental sciences.

4. Possible Electrical Artifacts

In some of the laboratories examined, the electrolytic cells were operated at constant voltage, not constant current. Since the conductivity of solutions of LiOD is only about half that of corresponding solutions of LiOH, and since the cells were operated in a regime where the applied voltage appeared as a drop across the solution resistance, cells operated with H₂O electrolyzed more moles per second than equivalent cells containing D₂O. In some data (e.g. temperature differential vs. applied power for cells in the two different solvents), this effect can show apparent excess heat for the cells evolving deuterium, simply because less power is carried out of the cell in the enthalpy of formation of vented products.

A careful consideration of measurements with thermocouples clearly illustrates the difficulty of precise measurements of evolved heat power. The excess heats reported by several groups normally correspond to about one half degree in temperature differential. The sensitivity of the thermocouples is typically about 40 microvolts per degree, hence the effect is represented by a dc signal on the order of 20 microvolts, readable with a meter precision of about 2 microvolts per reading, or about 3 microvolts for the difference of two readings. The scatter of data points in

various studies suggests that the actual precision no better than about half to one-third of the differential ascribed to excess heat. Precise measurement of the differential is, of course, only half the story. One also needs accurate measurements of dc voltages at these low levels. If there were an experimental bias inducing even a few microvolts at the thermocouple in the cell, one could see an apparent excess heat. Since the thermocouple is operated in the electric field caused by the resistance losses in solution, such an induced signal is a very real possibility.

The thermocouple is normally encased in a glass or ceramic tube containing a heat transfer medium (sometimes water). It is assumed to be electrically isolated from the solution, but a few microvolts of pickup are not beyond the realm of possibility. Since the electric fields are typically larger in D₂O solutions than in H₂O solutions, this effect could be relevant to the differences between cells operated in D₂O vs. H₂O. It would also explain why the excess heat power sometimes seems to be nearly linear with applied electrolytic power.

Corrosion of the thermocouple in the heat transfer fluid could also produce dc offsets large enough to yield an apparent excess heat, especially if the heat transfer fluid were a polar liquid such as water.

The precise, accurate measurement of temperature differentials via thermocouples at the level of quality required to confirm typically reported excess heats is an experimental challenge of a unrecognized and surprisingly high order.

5. Recombination of D₂ and O₂

An assumption in most cases for which positive heat effects are reported is that the gaseous products D₂ and O₂ are vented without recombination. It is widely recognized that any recombination of these products to regenerate deuterium oxide within the cell will produce heat that will appear as an excess, simply because of the correction for the enthalpy of the products. Many groups have guarded against this error by measuring the volumes of gases produced and comparing them with the expectations based on the charge passed through the cell. On the other hand, these measurements are sometimes not made at all, and in other cases they are not made with sufficient precision and accuracy to assure the absence of recombination at a level that could account for the thermal excess. In a surprising number of instances, the cells were operated with Pt or Pd surfaces exposed in the headspace above the solution. These are efficient catalytic surfaces and could be expected to produce a breakdown of the assumption of no recombination.

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October 10, 1989

TO: John R. Huizenga Chairman, ERAB Cold Fusion Committee
FROM: John Schiffer Physics Division
SUSJECT: Draft Chapter on Fusion Products

This draft is built out of material sent to me by Bigeleisen, Garwin, Hoffman, Lipman, and Koonin. I have made some arbitrary decisions to eliminate some details and simplify explanations.

I am sorry that I cannot be at the meeting on Thursday, October 12, and have asked Dick Garwin to act on my behalf. I will undertake to incorporate any comments for the final draft with the help of the working group.

The data on neutrons, charged particles, and tritium may have to be updated and checked -- the data quoted are meant to be representative and not all-inclusive. We may want to add a paragraph on limits from mass spectroscopy on He -- if that has become available in a sensible fashion. My own feeling is that these measurements are so insensitive that it confuses the issue to invoke them.

JS:jcg

Enclosure

OPTIONS: ACK LOG LONG NOTEBOOK *

Local options: Search RealNode

Date: 9 October 1989, 16:38:56 EDT

From: (R.L.Garwin (914) 945-2555) RLG2 at YKTVMV

IBM Fellow and Science Advisor to the Director of Research

P.O. Box 218

Yorktown Hts, NY 10598

To: SCHIFFER at ANLPHY

Jth P.

Subject: Oppenheimer-Phillips

Reply-To: RLG2 at YKTVMV

Reply-Bit: RLG2 at WATSON

Reply-Xin: rlg2@ibm.com

Under IIa, you have

"The Oppenheimer-Phillips... in this regard." But I don't like
the following 5 lines at all. Instead, I would write,

**Replacement text:

Deuteron-induced nuclear reactions against high-Z nuclei often resemble reactions induced by neutrons, with the proton a bystander. This occurs when the neutron "fringe" of the deuteron (falling off rapidly with distance, as befits a 2.2 MeV deuteron binding energy and a "reduced mass" of 0.5 for the neutron in the deuteron) still falls off more slowly than the deuteron wave function itself close to the nucleus. In the D-D case, the opposite is true-- the exponential falloff of the deuteron itself close to the deuteron partner being proportional to $(Vc \times Mr)^{0.5}$, where Vc is the repulsive potential energy (0.6 MeV) and Mr the d-d reduced mass (1.0). Similarly, the neutron wave function falls off (penetrates the deuteron nuclear binding potential) as $(Vd \times Mr')^{0.5}$ or $(2.2 \text{ MeV} \times 0.5)^{0.5}$. The deuteron wavefunction thus extends readily over a distance 1.35 times that of the neutron fringe, whereas the opposite must hold if Oppenheimer-Phillips is to have any influence. In any case, the O-P reaction would correspond to $n+d \rightarrow T + \gamma$, and the readily observable gamma ray is not seen.

End replacement text

John, I would insert the PdAg as follows:

"... overpower trip of the electrolyzer. Tritium and neutrons are observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd. Fig. . ."

Late-breaking news, which I will bring to the meeting:

'''Neutron emission during plastic deformation of deuterium-containing solids under pressure' by M.A. Yaroslavskii (Dokl. Akad. Nauk SSSR (Vol. 307) 369-370 July 1989) reports the detection of neutron bursts from 'rheological explosions' induced by rotating the anvils of a press on a rock sample to which grains of beryllium bronze and D2O have been added. Typically, 1000 pulses are detected in a burst, interpreted by the experimenter as arising from 10^{16} neutrons. (Excerpt of translation by D.H. McNeill)'''

John, I trust this completes my current assignment. Thanks for all of your efforts. Dick Garwin

100989.JPS

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